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UNITED STATES DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
NATIONAL OCEAN SERVICE

3/7/97

TO: Distribution
FROM: Ed Long, NOS/ORCA ERL
SUBJECT: Draft final report on sediment toxicity in South Carolina/Georgia estuaries.

Enclosed is your copy of the final report that I have sent to headquarters for review and publication. Because it is a draft and not yet published, some portions of the report may change slightly before it is published as a NOAA technical memorandum. Feel free to distribute this draft report, but, please be aware that it is a draft report and not the final, published version.

The report has been reviewed by the co-authors who participated in the study and this final draft reflects their/your comments and suggestions. If you find any errors or omissions, please bring them to my attention as there is time to correct them (phone 206 526-6338, fax 526-6865).

The data analyses are as comprehensive and complete as possible, thus, in part leading to a very large document. The published version will include the raw data as appendices; however, to save costs of copying they are not included in this version.

Thanks very much for your participation, hard work, and cooperation in this large study. I think we generated a very nice baseline of information on sediment quality in this region of the U.S. The data from this study also provided a major contribution to our national estimates of the spatial extent of toxicity in estuarine sediments.

The report should be published as a NOAA technical report within the next 2-3 months.

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NOAA Technical Memorandum NOS ORCA xx

National Status and Trends Program
for Marine Environmental Quality

Magnitude and Extent of Sediment Toxicity in Selected Estuaries of South Carolina and Georgia

Base Map From Fig. 1

DRAFT

Silver Spring, Maryland
April, 1997

NOAA National Oceanic and Atmospheric Administration

National Ocean Service
Office of Ocean Resources Conservation and Assessment
Coastal Monitoring and Bioeffects Assessment Division

NOAA Coastal Ocean Office

NOAA Technical Memorandum NOS ORCA xxx

Magnitude and Extent of Sediment Toxicity in Selected Estuaries of South Carolina and Georgia

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April, 1997

United States Department of Commerce	National Oceanic and Atmospheric Admin.	National Ocean Service	NOAA Coastal Ocean Office
Ronald H. Brown, Secretary	D. James Baker, Under Secretary	W. Stanley Wilson, Ass't Administrator	Donald Scavia, Director

Abstract

Surficial sediment samples were collected from 162 locations within five estuaries - Charleston Harbor, Winyah Bay, Leadenwah Creek, Savannah River, and St. Simons Sound - in coastal South Carolina and Georgia in a survey of sediment toxicity performed in 1993 and 1994. All samples were tested for toxicity with a battery of complimentary laboratory bioassays. The laboratory bioassays consisted of amphipod survival tests in solid-phase sediments, microbial bioluminescence (Microtox) tests of organic solvent extracts, and sea urchin fertilization and embryo development tests of porewaters. Some samples also were tested in copepod reproduction and cytochrome P-450 RGS bioassays. Chemical analyses for a suite of trace metals, organic compounds, and sedimentological factors were performed with portions of most samples.

In all five estuaries at least one bioassay showed significant toxicity in at least one sample. Toxicity in the amphipod tests, the least sensitive bioassay, was restricted to only a small minority of samples and was most severe in one sample each from a tributary to the St. Simons Sound and in the Savannah River. Toxicity was much more widespread in the other more sensitive bioassays. The incidence of toxicity was highest and the spatial extent of toxicity was greatest in Winyah Bay, intermediate in Charleston Harbor and Savannah River, and least prevalent and widespread in Leadenwah Creek and St. Simons Sound. Toxic conditions, as indicated with these tests, were scattered throughout each estuary. Some samples collected in the lower Ashley River, upper Cooper River, Georgetown Harbor, the upper Savannah River and harbors adjacent to downtown Savannah, and Brunswick Harbor/East River were notably toxic. However, each bioassay indicated different, but overlapping spatial patterns in toxicity and no major, unequivocal gradients in toxicity were apparent.

The concentrations of some trace metals exceeded background levels, exceeded some effects-based guidelines concentrations, and showed strong correlative associations with toxicity. The concentrations of many individual and classes of polynuclear aromatic hydrocarbons (PAHs) also were elevated in samples that were significantly toxic in some toxicity tests. The concentrations of chlorinated organic compounds (e. g., PCBs) were elevated in a few samples. Results of cytochrome P-450 RGS assays showed strong correlations with the concentrations of high molecular weight PAHs and PCBs. Toxicity tests performed with invertebrates and Microtox often indicated strong correlations with mixtures of potentially toxic substances, the composition of which differed among estuaries and toxicity tests. The concentrations of substances such as copper and high molecular weight PAHs showed evidence suggesting they could have contributed to toxicity. The concentrations of ammonia were sufficiently elevated only in a small minority of samples to contribute substantially to toxicity.

Overall, most samples (with some notable exceptions) from this survey area were somewhat less contaminated and toxic than those analyzed by NOAA from other US estuaries. The spatial extent of toxicity was somewhat lower than the nationwide averages estimated with data from over 20 large estuaries studied nationwide. These data, however, agreed well with observations from similar chemical analyses and toxicity tests performed by NOAA for the Environmental Monitoring and Assessment Program (EMAP)-Estuaries in the Carolinian province, which includes all five of these estuaries.

INTRODUCTION

Background. Toxic chemicals can enter the marine environment through numerous routes: stormwater runoff, industrial point source discharges, municipal wastewater discharges, atmospheric deposition, accidental spills, illegal dumping, pesticide applications and agricultural practices. Once they enter a receiving system, toxicants often become bound to suspended particles and increase in density sufficiently to sink to the bottom. Sediments are one of the major repositories of contaminants in aquatic envronments. Furthermore, if they become sufficiently contaminated sediments can act as sources of toxicants to important biota. Sediment quality data are direct indicators of the health of coastal aquatic habitats.

Sediment quality investigations conducted by the National Oceanic and Atmospheric Administration (NOAA) and others have indicated that toxic chemicals are found in the sediments and biota of some estuaries in South Carolina and Georgia (NOAA, 1992). This report documents the toxicity of sediments collected within five selected estuaries: Savannah River, Winyah Bay, Charleston Harbor, St. Simons Sound, and Leadenwah Creek (**Figure 1**).

As a component of its National Status and Trends (NS&T) Program, NOAA monitors toxicant concentrations in selected locations throughout the nation and surveys the biological significance of toxicant accumulations in selected regions. In the monitoring component of the program, mollusks and demersal fishes are captured annually for chemical analyses of their tissues. Sediments are collected and analyzed for a suite of metals and organic parameters. Spatial patterns and temporal trends in chemical concentrations are determined from the data (O'Connor and Ehler, 1991; O'Connor, 1991). Chemical analyses of sediments collected at each sampling site were performed at many of the sites the first year that each site was sampled. The monitoring activities were initiated in 1983 and have continued each year to the present time.

NS&T Program has analyzed oyster and sediment samples from the lower Winyah Bay, the Santee River, the lower Savannah River, and two sites in Charleston Harbor along with fishes and sediments from Charleston Harbor and lower Savannah River (Lauenstein et al., 1993). These data revealed that the concentrations of a number of chemicals were significantly elevated in sediments relative to background conditions. Detectable concentrations of PCBs, DDTs, chlordane, mirex, and polynuclear aromatic hydrocarbons (PAHs) occurred in sediment samples from these sites (NOAA, 1991). Many chlorinated pesticides also occurred in the tissues of resident oysters from the sites in South Carolina and Georgia (NOAA, 1989). The concentrations of some trace metals in some samples exceeded the concentrations expected in reference areas based upon normalization to aluminum content (Hanson and Evans, 1991). Concentrations of arsenic, cadmium, selenium, total PAHs,

tributyltins were particularly high in some areas and years (O'Connor and Baliaeff, 1995).

Furthermore, scattered among the estuaries of South Carolina and Georgia are a number of hazardous waste sites with very high chemical concentrations. One site adjacent to Purvis Creek in St. Simons Sound that was near a defunct chemical manufacturer had extremely high PCB and mercury concentrations in sediments and fish (Bronstein, 1995). Sediment and pore water samples from this area were toxic in laboratory tests and the toxicity was attributable, at least in part, to high concentrations of methylmercury and PCBs in the sediments (Winger et al., 1993). Several small sites in and adjacent to Charleston Harbor have had a history of elevated concentrations of different chemicals and have been the focus of remedial investigations (Heyward Robinson, Charleston Harbor Project, personal communication).

Analyses of age-dated sediment cores from the Savannah River estuary have shown a history of contamination by anthropogenic chemicals, including mercury, chromium, lead, PAHs, dieldrin, DDT and PCBs during the 1950s and 1960s (Alexander et al., 1994). Concentrations have gradually decreased during the past 20-30 years and recently-deposited, surficial sediments have lower chemical concentrations.

Sources of pollution in Charleston Harbor include industrial and municipal point sources, urban and suburban nonpoint sources, septic tank overflows, and runoff from forested urban and agricultural watersheds (Matthews et al., 1980). The number of permitted point sources in Charleston Harbor, however, have decreased from 115 in 1969 to 78 in 1986 (SCSGC, 1992; Davis and Van Dolah, 1992). Portions of Charleston Harbor, including the Ashley and Cooper rivers, have had relatively high concentrations of anthropogenic trace metals, PCBs and pesticides in the sediments.

There are 13 current point source discharges to Winyah Bay, including the discharges from the International Paper Mill which contained the highest concentrations of dioxins among mills surveyed in 1989 (DHEC, unpublished data). A health advisory that warned people not to eat fish and shellfish because of high dioxin concentrations in the Sampit River, a tributary to the Winyah Bay, was lifted in 1992 (South Carolina Department of Health and Environmental Control). Pesticide use in the Winyah Bay watershed has been very high relative to the size of the watershed (South Carolina Sea Grant Consortium, 1992). Kucklick and Bidleman (1994) reported high concentrations of several pesticides and PAHs in Winyah Bay.

Leadenwah Creek, a small tributary to the North Edisto River estuary, receives considerable agricultural runoff (Scott et al., 1990; 1993). Runoff of pesticides such as azinphosmethyl, endosulfan, and fenvalerate, from nearby vegetable farms has caused major fish kills, and other impacts to fish, oysters, and macropelagic fauna (Scott et al., 1988; Scott et al., 1993; Fulton, 1989). Toxicity of the sediment-associated pesticides fenvalerate and endosulfan to

meiobenthic animals has been demonstrated in laboratory tests performed with samples collected from Leadenwah Creek. Toxicity tests of fenvalerate included measures of reproductive success, in which depressed egg production and mean clutch sizes were observed in copepods (Chandler, 1990). Endosulfan inhibited larval colonization and early juvenile growth among polychaetes but did not appear to affect meiobenthic copepods (Chandler and Scott, 1991).

Current Survey Rationale. Because of the presence of anthropogenic chemicals in sediments and biological tissues, the relatively high risks of adverse effects to living marine resources, the documented urban and industrial development of the estuaries and a lack of information on toxicant effects, NOAA elected to study this area. Sediments were collected throughout the area over a two-year period to determine if there was an effect on biota based on the use of a battery of laboratory toxicity tests.

The objectives of the survey were to:

(1) determine the presence and severity of toxic responses;

(2) estimate the spatial extent of toxicity;

(3) identify spatial patterns of toxicity in each system; and

(4) characterize the relationships between toxicity and the concentrations of potential toxicants in the sediments.

Sampling and testing methods used in previous surveys performed elsewhere in the USA were employed in this survey. A wide variety of candidate measures of toxicant effects were evaluated and compared to determine which would be most useful in NOAA's surveys (Wolfe, 1992; Long and Buchman, 1989). Batteries of assays performed with sediments, bivalve molluscs, and demersal fishes in selected regions have been used to form a weight of evidence with regard to the presence and incidence of toxicant-associated bioeffects. Analyses of sediment toxicity have been included in these regional assessments to provide an estimate of potential effects of sediment contaminants on resident benthic populations. Batteries of toxicity tests appropriate for analyzing sediment toxicity were selected following evaluations of a number of candidates (Long and Buchman, 1989).

Thus far, sediment toxicity surveys have been performed by NOAA in San Francisco Bay (Long and Markel, 1992); Tampa Bay (Long et al., 1994); Long Island Sound (Wolfe et al., 1994); Hudson-Raritan estuary (Long et al., 1995); Boston Harbor (Long et al., in press); Los Angeles/Long Beach Harbor (Sapudar et al., 1994); San Diego Bay (Fairey et al., 1996); western Florida panhandle (Sloane et al., in press); and in several other areas in which the surveys are still underway.

Study Area. The study area included Winyah Bay, Charleston Harbor, Leadenwah Creek, Savannah River, and St. Simons Sound (**Figure 1**). In Winyah Bay the study area included the lower Sampit River, Georgetown

Harbor, and lower Winyah Bay seaward to approximately the junction with the Intracoastal Waterway (**Figure 2**). The Charleston Harbor survey area included the Ashley River below I-95, the Cooper River from approximately Goose Creek, and Wando River from approximately Nowell Creek, Charleston Harbor, and stretched seaward to the mouth of the harbor at Fort Sumter (**Figure 3**). In Leadenwah Creek, samples were collected from the head of the creek to its junction with the North Edisto River estuary (**Figure 4**). In the Savannah River the study area extended from approximately Interstate - 95 to the mouth of the river and included several industrial harbors and the south river channel that parallels the Savannah River seaward to approximately Cockspur Island (**Figures 5**). In St. Simons Sound the study area included the lower Turtle River, Brunswick Harbor (East River), Brunswick River, the Back River, Terry Creek, the lower estuary seaward to the mouth of the bay (**Figure 6**). As described below in Methods, each of the five study areas was stratified (sub-divided) into approximately equal strata and samples were collected from randomly-chosen locations.

METHODS

Sampling Design. Five estuaries were investigated during 1993 and 1994: Charleston Harbor, Winyah Bay, and Leadenwah Creek were sampled during May-June, 1993, and St. Simons Sound and Savannah River were sampled in June-July, 1994. The same sampling procedures, boat, and crew were used in both years.

The study area included saltwater portions of these five estuaries. Stratified, random sampling designs patterned after those of the EMAP-Estuaries surveys (Schimmel et al., 1994) were used in each area during the selection of sampling stations. Each bay was subdivided into irregular-shaped strata. Large strata were established in the open waters of the bays where toxicant concentrations were expected to be uniformly low. This approach provided the least intense sampling effort in areas known or suspected to be relatively homogenous in sediment type and water depth and relatively distant from contaminant sources. In contrast, relatively small strata were established in urban harbors, bayous and tributaries nearer suspected sources in which conditions were expected to be heterogeneous or transitional. Sampling effort was more intense in the small strata than in the large strata. The large strata were roughly equivalent in size to each other and the small strata were roughly equivalent in size to each other.

This approach combines the strengths of a stratified design with the random-probabalistic selection of sampling locations. Data generated within each stratum can be attributed to the dimensions of the stratum. Therefore, these data can be used to estimate the spatial extent of toxicity with a quantifiable degree of confidence (Heimbuch, et al., 1995). Strata boundaries were established to coincide with the dimensions of major basins, bayous, waterways, etc. in which hydrographic, bathymetric and sedimentological conditions were expected to be relatively homogeneous.

The locations of individual sampling stations within each strata were chosen randomly using the EMAP computer software and hardware (Dr. Kevin Summers, U. S. EPA, Environmental Research Laboratory, Gulf Breeze, FL). One to three samples were collected within each stratum. Usually, four alternate locations were provided for each station in a numbered sequence. The coordinates for each alternate were provided in tables and were plotted on the appropriate navigation chart. In a few cases the coordinates provided were inaccessible. They were rejected and the vessel was moved to the next alternate.

Sample Collection. At each station the sampling vessel was piloted to the first alternate location for the sample collection. If the station was inacessible or if the material at the location was only coarse sand and gravel with no mud (silt+clay) component, that alternate location was abandoned and the

second (third, or fourth, if needed) alternate was sampled. In almost all cases the first or second alternates were acceptable and were sampled.

Vessel positioning and navigation were aided with a Trimble NavGraphic XL Global Positioning System (GPS) unit and a compensated LORAN C unit. Both systems generally agreed very well with each other when both were operational. Both were calibrated and their accuracy verified each morning at a channel marker within the study area.

Samples were collected with a Kynar-lined 0.1m^2 modified van Veen grab sampler (also, known as a Young grab) deployed with an electric windless aboard the state of Florida R/V *Raja*. The grab sampler and sampling utensils were acid washed with 10% HCl at the beginning of each survey, and thoroughly cleaned with site water and acetone before each sample collection. Usually, 3 or 4 deployments of the sampler were required to provide a sufficient volume of material for the toxicity tests and chemical analyses. The upper 2-3 cm. of the sediment were sampled to ensure the collection of recently-arrived materials. Sediments were removed with a plastic scoop and accumulated in a stainless steel pot. The pot was covered with a Teflon plate between deployments of the sampler to minimize sample oxidation and exposure to shipboard contamination. The material was carefully homogenized in the field with a stainless steel spoon before it was distributed to prepared containers for each analysis.

The portions of samples to be tested for amphipod survival and sea urchin bioassays were shipped in 2 gal. polyethylene jugs. Portions for Microtox tests were shipped in 100 mL glass jars and portions for chemical analyses were shipped in pre-cleaned, 250 mL I-Chem glass jars with Teflon lids. Jars and lids were labelled with information on sample and station numbers.

Samples were shipped in ice chests packed with water ice or blue ice to the testing laboratories by overnight courier. They were accompanied by chain of custody forms and station labels.

Locations of the individual sampling stations in each area are illustrated in Figures 7-13, and coordinates for each are listed in Appendix A. Field log notes containing information on depth and sediment characteristics at each station are also listed in Appendix A. A total of 162 samples were tested for toxicity in this survey. In Charleston Harbor 63 samples were collected, 52 chosen randomly by NOAA and 9 chosen for specific locations by the Charleston Harbor Project (CHP) (Figure 7). Samples were collected along the Ashley, Cooper, and Wando rivers, throughout Charleston Harbor, and seaward through the lower harbor to Fort Sumter (Figure 7). Nine samples were collected in Leadenwah Creek, a tributary to the North Edisto River previously impacted by agricultural runoff (Figure 8). In Winyah Bay nine samples were collected in the lower Sampit River, Georgetown Harbor, and

upper Winyah Bay (Figure 9). In St. Simons Sound 20 samples were collected from locations in the Turtle River, Brunswick Harbor, Terry Creek, Back River, and St. Simons Sound (Figure 10). In the Savannah River 60 samples were collected throughout three different segments of the system: from the mouth of the river to Fort Johnson (Figure 11), from Fort Johnson to Port Wentworth (Figure 12), and upstream above Port Wentworth (Figure 13). One sample was collected in a reference area, North Inlet-Oyster Landing, north of Charleston.

Multiple toxicity tests were performed on all sediment samples. Chemical analyses were performed on a subset of samples from each estuary for trace metals, butyl tins, polynuclear aromatic hydrocarbons, chlorinated pesticides and PCBs following a review and evaluation of the toxicity test results. Amphipod survival tests were performed by the National Biological Service (now U.S. Geological Survey) laboratory in Corpus Christi, TX. and Science Applications International Corporation in Narragansett, RI. Microtox bioluminescence tests and chemical analyses were performed by the National Marine Fisheries Service laboratory of NOAA in Charleston, SC. Sea urchin fertilization tests were performed by the National Biological Service (now U.S. Geological Survey) laboratory in Corpus Christi, TX. Copepod reproduction tests were performed by the University of South Carolina in Columbia, SC. Cytochrome P-450 RGS bioassays were performed by Columbia Analytical Services in Carlsbad, CA.

Amphipod Survival Test. The amphipod tests are the most widely and frequently used assays in sediment evaluations performed in North America. They are performed with adult crustaceans exposed to relatively unaltered, bulk sediments. *Ampelisca abdita* has shown relatively little sensitivity to nuisance factors such as grain size, ammonia, and organic carbon in previous surveys. In previous surveys, the NS&T Program has observed wide ranges in responses among samples, strong statistical associations with toxicants, and small within-sample variability (Long et al., 1994; Wolfe et al., 1994; Long et al., 1995).

Ampelisca abdita is a euryhaline benthic amphipod that ranges from Newfoundland to south-central Florida, and along the eastern Gulf of Mexico. The amphipod test with *A. abdita* has been routinely used for sediment toxicity tests in support of numerous EPA programs, including EMAP in the Virginian, Louisianian, and Carolinian provinces (Schimmel et al., 1994). Amphipod toxicity tests followed ASTM protocols (ASTM, 1990,1992). In the first year, amphipod tests of samples from Charleston Harbor, Winyah Bay, and Leadenwah Creek were conducted by the National Biological Service (NBS) laboratory. In the second year amphipod assays were conducted by Science Applications International Corporation, (SAIC).

In year one, test animals were purchased from Brezina and Associates of Dillon Beach, California. Amphipods were packed in native sediment with 8-10 liters of seawater in doubled plastic bags. Oxygen was injected into the bags and shipped via overnight courier to the testing lab at Port Aransas. Upon arrival, amphipods were acclimated and maintained at 20°C for one day prior to the initiaton of the test.

Control sediments for year one testing included sediment collected from the natural habitat of the amphipods in California, and a reference sediment from Redfish Bay, Texas. The Redfish Bay sediments had been used in previous sediment quality assessment studies by the U.S. Fish & Wildlife Service (then, NBS, now USGS). Both the control and reference sediments were handled in the same manner as the samples from South Carolina.

For year two testing, amphipods were collected by SAIC from tidal flats in the Pettaquamscutt (Narrow) River, a small estuary flowing into Narragansett Bay, Rhode Island. Animals were held in the laboratory in pre-sieved uncontaminated ("home") sediments under static conditions. Fifty percent of the water in the holding containers was replaced every second day when the amphipods were fed. During holding, *A. abdita* were fed laboratory cultured diatoms (*Phaeodactylum tricornutum*).

Control sediments were collected by SAIC from the Central Long Island Sound (CLIS) reference station of the U.S Army Corps of Engineers, New England Division. These sediments have been tested repeatedly with the amphipod survival test and other assays and found to be non-toxic (amphipod survival has exceeded 90% in 85% of the tests) and un-contaminated (Wolfe et al., 1994; Long et al., 1995). Sub-samples of the CLIS sediments were tested along with each series of samples from Savannah River and St. Simons Sound.

Amphipod testing performed by both laboratories followed the procedures detailed in the Standard Guide for conducting 10 day Static Sediment Toxicity Tests with Marine and Estuarine Amphipods (ASTM, 1990, 1992). Briefly, amphipods were exposed to test and negative control sediments for 10 days with 5 replicates of 20 animals each under static conditions using filtered seawater. For the NBS test, 250 mL of test or control sediments were delivered into 1-liter glass jars, and 700 mL of seawater were added to each jar. The SAIC procedure differed somewhat: 200 mls of test or control sediments were placed in the bottom of the test chamber, and covered with approximately 600 mL of filtered seawater (28-30 ppt). For both sets of tests, air was provided by air pumps and delivered into the water column through a pipette to ensure acceptable oxygen concentrations, but suspended to ensure that the sediments would not be disturbed. Temperature was maintained at ~20°C by either incubator (NBS) or water bath (SAIC). Lighting was

continuous during the 10 day exposure period to inhibit the swimming behavior of the amphipods. Constant light inhibited emergence of the organisms from the sediment, thereby maximizing the amphipod's exposure to the test sediments.

Twenty healthy, active animals were placed into each test chamber, and monitored to ensure they burrowed into sediments. Non-burrowing animals were replaced, and the test initiated. The jars were checked daily, and records kept for dead animals, and animals on the water surface, emerged on the sediment surface, or in the water column. Those on the water surface were gently freed from the surface film to enable them to burrow, and dead amphipods were removed.

Tests were terminated after ten days. Contents of each of the test chambers were sieved through a 0.5 mm mesh screen. The animals and any other material retained on the screen were examined under a stereomicroscope for the presence of amphipods. Total amphipod mortality was recorded for each test replicate.

During year 1 the NBS laboratory ran tests in two batches of 41 and 42 samples each with holding times of <10 days and <15 days, respectively. Sample holding times for most tests in year 2 were <8 days; however, due to poor performance in negative controls some samples were re-tested and holding times ranged up to 38 days. A positive control test was used to document the sensitivity of each batch of test organisms. The positive control consisted of 96 hr water-only exposures to sodium dodecyl sulfate (SDS). LC50 values were calculated for each test run.

Sea Urchin Fertilization and Embryological Tests. Tests of sea urchin fertilization and embryo development have been used in assessments of ambient water and effluents and in previous NS&T Program surveys of sediment toxicity (Long et al., 1994; Carr et al., 1996). Test results have shown wide ranges in responses among test samples, excellent within-sample homogeneity, and strong associations with the concentrations of toxicants in the sediments. The tests, performed with the early life stages of sea urchins, have demonstrated high sensitivity.

Toxicity of sediment pore waters were conducted with the sea urchin *Arbacia punctulata*. These tests were performed during both years by the National Biological Service (NBS), National Fisheries Contaminant Research Center in Corpus Christi, Texas at their laboratory located in Port Aransas. Sea urchins used in this study were obtained either from jetties at Port Aransas, Texas, or from Gulf Specimen Company, Inc. (Panacea, Florida), and were acclimated to Port Aransas seawater before gametes were collected for testing.

Pore water was extracted from sediments with a pressurized squeeze extraction device (Carr and Chapman, 1992). Sediment samples were held refrigerated (at 4° C) until pore water was extracted. Pore water was extracted as soon as possible after receipt of the samples, but in no event were sediments held longer than 7 days from the time of collection before they were processed. After extraction, porewater samples were centrifuged in polycarbonate bottles (at 4200 g for 15 minutes in year one, and in year two using a new centrifuge - 1200 g for 15 minutes was adequate) to remove any particulate matter, and were then frozen. Two days before the start of a toxicity test, samples were moved from a freezer to a refrigerator at 4° C, and one day prior to testing, thawed in a tepid water bath. Experiments performed by NBS have demonstrated no effects upon toxicity attributable to freezing of the pore water samples.

Sample temperatures were maintained at 20±1° C. Sample salinity was measured and adjusted to 30±1 ppt, if necessary, using ultrapure sterile water or concentrated brine. Other water quality measurements were made for dissolved oxygen, pH, sulfide and total ammonia. Temperature and dissolved oxygen were measured with YSI meters; salinity was measured with Reichert or American Optical refractometers; pH, sulfide and total ammonia (expressed as nitrogen, TAN) were measured with Orion meters and their respective probes. The concentrations of un-ionized ammonia (UAN) were calculated using respective TAN, salinity, temperature, and pH values.

Each of the porewater samples was tested in a dilution series of 100%, 50%, and 25% of the water quality adjusted sample with 5 replicates per treatment. Dilutions were made with clean, filtered (0.45 um), Port Aransas laboratory seawater. Tests followed the methods of Carr and Chapman (1992). Pore water from a reference area in Redfish Bay, Texas, an area located near the testing facility and in which sediment porewaters have been determined to be non-toxic in this test (e. g., Long et al., 1994), was included with each toxicity test as a negative (non-toxic) control. Adult male and female urchins were stimulated to spawn with a mild electric shock, and gametes collected separately.

For each test, 50 uL of 1:5000 diluted sperm were added to each vial with 5 mL of porewater sample and incubated at 20±2°C for 30 minutes. One ml of a well mixed dilute egg suspension was added to each vial, and incubated an additional 30 minutes at 20± 2°C. Two mls of a 10% solution of buffered formalin solution was added to stop the test. Fertilization membranes were counted after the 1-hour exposures and fertilization percentages calculated for each replicate test. In the embryological tests, 100 embryos were examined in each replicate after 48-hour exposures to pore water. Both percent normal and percent abnormal embryological development were recorded for each

porewater concentration (100%, 50%, and 25%) following methods of Carr et al., 1996.

Microbial bioluminescence (Microtox™) tests. This is a test of the relative toxicity of extracts of the sediments prepared with an organic solvent, and, therefore, it is immune to the effects of nuisance environmental factors, such as grain size, ammonia and organic carbon. Organic toxicants, and to a lesser degree trace metals, that may or may not be readily bioavailable are extracted with the organic solvent. Therefore, this test can be considered as a test of potential toxicity. In previous NS&T Program surveys, the results of Microtox tests have shown extremely high correlations with the concentrations of mixtures of organic compounds (Long et al., 1994; Long et al., 1995; Wolfe et al., 1994).

The Microtox® assay was performed with dichloromethane (DCM) extracts of sediments following the basic procedures used in testing Puget Sound sediments (U.S. EPA, 1986, 1990, 1994) and San Fransisco Bay sediments (Long and Markel, 1992). All sediment samples were stored in the dark at 4°C for 5-10 days before processing was initiated. A 3-4 g. sediment sample from each station was weighed, recorded, and placed into a DCM rinsed 50 mL centrifuge tube. A 15 g portion of sodium sulfate was added to each sample and mixed. Pesticide grade DCM (30 ml) was added and mixed. The mixture was shaken for 10 seconds, vented and tumbled overnight.

Sediment samples were allowed to warm to room temperature and the overlying water discarded. Samples were then homogenized with a stainless steel spatula, and 15-25 grams of sediment were transferred to a centrifuge tube. The tubes were spun at 1000 g for 5 min. and the pore water was removed using a Pasteur pipette. Three replicate 3-4 g sediment subsamples from each station were placed in mortars containing a 15 g portion of sodium sulfate and mixed. After 30 min. subsamples were ground with a pestle until dry. Subsamples were added to 50 mL centrifuge tubes. Then, 30 mL of DCM were added to each tube and shaken to dislodge sediments. Tubes were then shaken overnight on an orbital shaker at a moderate speed. Tubes were then centrifuged at 500 g for 5 min and the sediment extracts transferred to Turbovap™ tubes. Then, 20 mL of DCM was added to sediment, shaken by hand for 10 sec and spun at 500 g for 5 min. The previous step was repeated once more and all three extracts were combined in the Turbovap™ tube. Sample extracts were then placed in the Turbovap™ and reduced to a volume of 0.5 mL. The sides of the Turbovap™ tubes were then rinsed down with methylene chloride and again reduced to 0.5 mL. Then, 2.5 mL of dimethylsulfoxide (DMSO) were added to the tubes which were returned to the Turbovap™ for an additional 15 min. Sample extracts were then placed in clean vials and 2.5 mL of DMSO were added to obtain a final volume of 5 mL DMSO.

A suspension of luminescent bacteria, *Vibrio fischeri*, (Azur Environmental, Inc.) was thawed and hydrated with toxicant-free distilled water, covered and stored in a 4°C well on the Microtox analyzer. To determine toxicity, each sample was diluted into four test concentrations. Percent decrease in luminescence of each cuvette relative to the reagent blank was calculated. Based upon these data, the sediment concentrations that caused a 50% decrease in light production (EC50's) were reported.

A negative control (extraction blank) was prepared using DMSO, the test carrier solvent. A phenol standard (45 mg/L phenol) was run after re-constitution of each vial of freeze-dried *V. fischeri*. In addition, a reference sediment was tested from North Inlet - an area shown to be non-toxic in sensitive laboratory tests in previous studies.

Copepod Reproduction Tests. Fourteen-day, chronic tests of reproductive success of the meiobenthic copepod *Amphiascus tenuiremis* were performed on 14 selected samples. The fourteen samples were selected to represent a presumed pollution gradient within Charleston Harbor. Analyses followed the standard protocols of Chandler (1990), Chandler and Scott (1991) and Strawbridge et al. (1992). Samples were press-seived (0.125 mm) to remove meiofauna and large particles; 12 gram sieved aliquots were extruded into triplicate beakers filled with clean sterile-filtered artificial seawater. Then, 35 barren females and 15 males were removed from stock cultures and added to each beaker. Flow-through exposures were conducted for 14 days. Test animals were fed phytoplankton (*Isochrysis galbana* and *Dunaliella tertiolecta*) on days 3, 6, 9, and 12. Barriers consisting of 0.045 mm mesh screens prevented animal losses. After 14 days all males, females, clutch sizes and offspring were counted and compared with North Inlet negative controls.

Toxicological end-points included survival of adults at the end of 14 days, naupliar production (no. nauplia per sample), copepodite production (no. copepodites per sample), clutch size (no. eggs per gravid female per sample), and total production (total no. nauplii + copepodites per sample). Results were initially analyzed using SAS ANOVA/GLM (F statistic) and Tukey's Studentized Range Test ($p<0.05$).

Cytochrome P-450 RGS Assays. This assay of the light produced by luciferase in a reporter gene system (RGS) of cultured human liver cells was conducted on selected samples from Charleston Harbor and Winyah Bay. The assay has been responsive to the presence of mixed-function oxidase inducers such as dioxins, furans, high molecular weight PAHs, and coplanar PCBs in tissues and sediments (Anderson et al., 1995). The induction of cytochrome P-450 RGS by sediment extracts was determined in 29 samples selected to represent a gradient in response in the amphipod, Microtox and urchin tests.

In these tests, standard protocols (Anderson et al., 1995, 1996; ASTM, 1997; APHA, 1996) were followed to ensure comparability with data derived for other areas. Approximately, 20 g of sediment from each station were extracted by EPA method 3540 to produce 1-2 mL of DCM/ extract mixture. Small portions of these samples (2-10 uL) were applied to approximately one million human liver cells contained in three replicate wells with 2 mL of culture medium. After 18 hours of incubation, the cells were washed, then lysed, the solution centrifuged following EPA method 3540 to produce 2 mL extracts of dichloromethane. Small portions (10 mL) were used in measures of luminescence. Solvent blanks and the reference toxicant (2, 3, 7, 8 - dioxin) were tested with each batch of samples. The relative light unit (RLU) from the solvent blank was set equal to unity and all other RLUs were divided by (normalized to) that of the blank. The running average fold induction for 10nM dioxin is approximately 140 and the induction from 1 mg/ml of benzo(a)pyrene (b[a]p) was 60 fold. Data were converted to mg of b(a)p equivalents per g of sediment by multiplying the response (fold induction) from 10 mL of extract by a factor (200) to represent the total of inducing substances in the 2 mL extract, and then dividing by the factor of 60 and the dry wt. of the sample.

Chemical Analyses. Sediment samples were chosen for chemical analyses based upon an examination of the toxicity test results. Samples were chosen that represented gradients in the toxicity results and that, also, represented contiguous geographic stations. Chemical analyses were performed by the National Marine Fisheries Service laboratory, Charleston, SC. Analytical methods followed performance-based analytical protocols and employed quality-assurance steps of the NS&T Program (Lauenstein and Cantillo, 1993).

Extraction for organic analyses: The methods for extraction and sample preparation are similar to those of Krahn *et al.* (1988) with few modifications. Approximately 8.5 g of sediment was dried by mixing with 100 g of Na_2SO_4, which had been ashed for 16 h at 700°C. The dried sample was transferred to a Pyrex Soxhlet thimble and the internal standards D_8-napthalene (200 ng), D_{10}-acenapthalene (200 ng), D_{10}-phenanthrene (502 ng), D_{10}-fluoranthene (497 ng), D_{12}- perylene (102 ng), dibromooctafluorobiphenyl (DBOFBP; 20 ng), 2,2',4,5',6-pentachlorobiphenyl (PCB-103; 20 ng) and 2,2',3,3',4,5,5',6-octachlorobiphenyl (PCB-198; 20 ng) were added. The sample was then extracted in a Soxhlet apparatus with 250 mL of CH_2Cl_2 for 18 h. Sample extracts were reduced in volume by a stream of purified nitrogen using a nitrogen blow-down concentrator (Turbo Vap, Zymark Instruments) to *ca.* 0.5 mL. Lipids and other high molecular weight compounds were removed from the sample by gel permeation chromatography. The liquid chromatograph consisted of an autosampler (Gilson Model 231), a Waters

HPLC pump (model 501), two 22.5 x 500 mm gel permeation columns in series (Phenomenex Phenogel, 100 Å pore size), a UV detector (Linear model UV-106) and a fraction collector (Gilson model 201). The mobile phase was CH_2Cl_2 at a flow rate of 7 mL/min. 400 mL of the sample was injected into the system with lipids and other high molecular weight compounds eluting in the first 14 minutes. The fraction of interest was collected beginning 1 min before the retention time of DBOFBP and ending 2 min after perylene. The resulting fraction was reduced in volume as above and the CH_2Cl_2 was replaced with hexane and concentrated to a final volume of *ca.* 0.5 mL. At this point, elemental sulfur was removed from the sample by treatment with activated copper. To remove remaining polar interferences, the sample was then transferred to a 6 g cyanopropyl solid phase extraction cartridge (Varian, prerinsed with 6 mL of hexane) and eluted with 12 mL of hexane.

Polycyclic aromatic hydrocarbon (PAH) analysis: PAHs were quantified by two methods, capillary GC-ITMS and HPLC with fluorescence detection. Details of the analytes measured, internal standards, quantitation ions (GC-ITMS) and fluorescence excitation and emission wavelengths (HPLC-fluorescence) are available from NOAA. The instrument used for the GC-ITMS analysis was a Finnigan MAT Magnum Ion Trap Mass Spectrometer equipped with a Varian 3400 gas chromatograph and Varian 8200 autosampler. The column was a 30 m x 0.25 mm (i.d) DB-5ms (J&W Scientific) with a film thickness of 0.25 mm. The carrier gas was helium at a linear velocity of 33 cm/sec at 300 ^{o}C. The temperatures were 280^{o}C, 220^{o}C and 280^{o}C for the injection, ion source and transfer line, respectively. The acquisition scan range was from 50-285 amu with a scan rate of 0.6 sec/scan. The sample was injected (1 mL) using a splitless Grob technique (1 minute split time) at an initial oven temperature of 45^{o}C. After a one minute hold, the oven was ramped to 110^{o}C at 25^{o}C/min (one minute hold), ramped to 300 ^{o}C at 10^{o}C/min then finally ramped to 320 ^{o}C with a 3.5 minute hold. The instrument was calibrated using a mixed standard of the analytes with the internal standards injected at five concentrations. The calibration was verified at the start an end each sample sequence and every 8 hours in between using a mid-level calibration standard and recalibrated as necessary. The target analytes were identified both by the GC retention time window (15 sec) and the presence and ratios of fragmentation ions relative to the molecular ion.

PAHs were additionally quantified using HPLC with fluorescence detection utilizing a method similar to Wise *et al.* (1988) and Schantz *et al.* (1990). The instrument consisted of two HPLC pumps (Waters 6000A), a 680 gradient controller (Waters model 680) and an autosampler (Waters WISP). The column dimensions were 6 mm X 25cm, with a 5 mm particle size (Supelco LC-PAH) and the column was

heated to 30°C (Fiaton TC-50 column heater controller and a CH-30 column heater). The solvent was pumped at a constant flow rate of 1.5 mL/min with a gradient program that started with a two minute hold at 60% water:40% acetonitrile followed by a linear ramp to 55% water:45% acetonitrile in 15 minutes and a final ramp to 0 % water:100% acetonitrile in 35 minutes with a 10 minute hold. Fluorescence was monitored with two fluorescence detectors (Perkin Elmer LC-240 and LS-4) connected in series at wavelengths specific to individual PAHs. The separation between deuterated and nondeuterated PAHs was 0.44, 0.40 and 0.41 min for phenanthrene, fluoranthene and perylene, respectively. A NIST certified PAH standard solution and the deuterated PAH internal standards were used to calibrate the instrument. Sample peaks were identified by retention times and fluorescence specific wavelength.

Organochlorine and pesticide analysis: Chlorine-containing compounds were analyzed using gas chromatography with electron capture detection (GC-ECD; Hewett-Packard 5890 series II). The instrument was configured with two columns, a 30 m x 0.25 mm i.d. (0.25 mm film thickness) DB-5 (5% phenyl; J&W Scientific) and a column with the same dimensions and 50% phenyl (Rtx-50; Restek Corp.). The carrier gas was held at a constant avererage linear velocity of 33 cm/sec by pressure programming the injector. The carrier and detector makeup gasses were helium and argon:methane (95%:5%), respectively. The injector and detector temperatures were 250 and 320°C, respectively. The sample was injected (2 mL) using a splitless Grob technique (1 min split time). The sample was then split such that nearly equal portions were sent to each column. The initial oven temperature was 50°C with a one minute hold, followed by a ramp to 170°C at 4°C/min, then from 170°C to 210°C at 1°C/min then from 210 to 310°C at 4°C/minute with a 10 min hold.

The instrument was calibrated using a mixed standard of the target analytes (chlorinated pesticides, NIST SRM 2261; and PCB congeners, NIST/NOAA intercalibration mixture) prepared with the internal standards (DBOFBP, PCB 103 and PCB 198). The standard was prepared in three concentrations that bracketed the sample concentrations. The calibration curve was verified at the beginning of each sample set by injecting the mid-level coninuing calibration a check standard which was required to be within Å20% of the known value for each analyte or the instrument was recalibrated. Retention data was simultaneously acquired from the two columns and was used to identify the analytes. On each column, unknown peaks were identified relative to that in the standard. If the unknown analyte peak fell within Å0.05 minutes of the standard and was present on both columns, then the peak was determined to be

authentic. The analyte amount was determined on each column and the lower amount was reported.

Extraction for metals analyses: From the original sample, 20 g was transferred to a 30 mL acid-washed plastic sample cup then the sediment and cup were weighed to 0.0001 g. The sample was then covered and dried at 70°C for 24 h. After drying, the sample was reweighed to determine percent moisture. The dried sediment was then ground with a mortar and pestle and transferred to a 20 mL plastic screw-top container.

Samples were extracted using a closed-vessel, concentrated acid microwave digestion technique. A 0.5 g subsample of the ground sediment was weighed (0.0001 g) into a Teflon-lined digestion vessel. To this, 10 mL of concentrated HNO_3 (Instra-analyzed) plus 0.5 mL deionized water was added to the vessel. The sample was then microwaved using a well ventilated, 600 watt corrosion-resistant digestion microwave (CEM Model MDS-2000) for 2 hours at full power and 120 psi. The sample was allowed to cool, then 2.0 mL of 30% H_2O_2 was added to the vessel, which was then microwaved for an additional 10 min at full power and 80 psi. After cooling, the digestate was filtered (#41 filter paper) into a 50 mL volumetric flask and brought to volume with deionized water. The sample was then transferred by pouring into a 50 mL polypropylene conical centrifuge tube for analysis.

A separate extraction procedure was used for Hg. From the dried sediment sample, 0.2 to 0.5 g of sediment was weighed (0.0001 g) then transferred to a 300 mL biological oxygen demand bottle (BOD). To the bottle, 5 mL, 1.25 mL and 3.75 mL of deionized water, HNO_3, and HCl were added, respectively. The bottles were then placed in a 95 Å 5 °C water bath for 2 min. The bottles were removed, cooled to room temperature then 50 mL deionized water and 15 mL 5% $KMnO_4$ (w/v) solution was added to the BOD bottle. The bottle was then returned to the water bath for an additional 30 min, removed, and allowed to cool for at least 1 h. The bottles were then uncapped and 6 mL of a NaCl-hydroxyamine hydrochloride solution (12 g NaCl + 12 g hydroxyamine hydrochloride) and 55 mL deionized water were added.

Metals Analysis: A suite of metals (Al, As, Cd, Cr, Cu, Fe, Pb, Mn, Ni, Sn, Zn) were analyzed by inductively coupled plasma spectroscopy (ICP). The instrument (Perkin Elmer Plasma 1000 with autosampler) was calibrated initially by developing a standard curve for each element. The concentrations used spanned two orders of magnitude, with the lowest concentration being the method blank. The response factor was determined as the slope of the standard curve line (absorbance/mg metal). Prior to samples analysis, the calibration standards were analyzed to verify the standard curve. The check standards were a solution of Zn (5 mg/L),

Cd (2 mg/L), Cr , Cu, and Ni (1 mg/L each), a solution of Al (100 mg/L), Fe (50 mg/L) and individual standards of Mg (10 mg/L), As (1 mg/L) and Sn (100 mg/L). In addition to the above calibration standards, a solution was analyzed with the concentration equal to the midpoint the calibration curve for each metal to evaluate drift from the original calibration curve. This same standard was diluted 5:1 with deionized water as an interference check solution. Lastly, a quality control sample (SRM Marine Sediment MESS-2 from the National Research Board of Canada) was analyzed. The samples extracts were then analyzed in duplicate and the results averaged.

The metals Ag, As, Cd, Pb, and Se were analyzed by graphite furnace atomic absorption (graphite furnace-AA). A Perkin Elmer 5100 Atomic Absorption Spectrometer with a Zeeman HGA 600 Graphite Furnace was used for analyses. Prior to sample analysis, the instrument was calibrated with five separate concentrations of each metal spanning approximately 1 order of magnitude. The modifier $Mg(NO_3)_2$ was used for Ag, As, and Cd; $Ni(NO_3)_2$ for Se and PO_4-$Mg(NO_3)_2$ modifier for Pb. Samples were analyzed in duplicate and the results averaged.

Mercury was analyzed by cold-vapor atomic absorption using a Leeman Labs PS200 mercury analyzer at a wavelength of 253.7 nm. Prior to sample analysis, a five point calibration curve was constructed. Samples were analyzed in duplicate and the Hg concentration determined from the slope of the calibration curve and the sample absorption.

Acid Volatile Sulfide (AVS) and Simultaneously Extractable Metals (SEM) Analyses: The general procedure for measuring AVS and SEMs was based on Allen *et al.* (1991) with a few modifications. The analytical train for releasing sulfide and metals from sediment consisted of a N_2 gas supply segment, and a reaction/trap segment. Nitrogen was supplied by a tank of compressed high-purity nitrogen which flowed through two 500 ml gas-washing bottles and then to floating-ball flow meters positioned immediately before the 6 individual reaction/trap segments in series. The first gas washing bottle in the nitrogen segment contained a solution of vanadous chloride (VCl_2), while the second bottle contains de- aerated, deionized water. A third empty gas washing bottle was incorporated to restrict liquids from traveling down line. The reaction/trap portion consisted of a 500 mL round-bottom flask with a septum inlet and a glass tubing inlet/outlet and two traps (impingers). The round-bottom flask contained the sediment sample, water and 20 mL of 6 M HCl added to the flask to volatilize the sulfide and metals. The two impingers contained 0.5 M NaOH to trap the H_2S generated in the reaction in the round bottom flask after the HCl addition. The extaction lined contined six sample trains (round bottom flask + 2 traps) each controlled by an independent gas flow meter. The recovery of the trap system of AVS was 85% based on blanks

amended with standardized sodium sulfite solution. To measure AVS, *ca.* 5 g of wet homogenized sediment was weighted into the boiling flask. Deionized water (80 mL) was then added to the flask with a small Teflon-coated stir bar. This was connected to the line and the HCl-addition port sealed with a rubber septum. The sediment-deionized water mixture was then purged with nitrogen for 10 minutes to remove residual oxygen. The flow was then stopped then 20 mL of 6M HCl was added to each flask through the septum via a syringe. The sample was stirred with a magnetic stirrer and the reaction was allowed to proceed for 1.5 h. After the reaction was complete, the solution in each boiling flask was filtered through a 0.45 mm membrane filter (Gelman Sciences), with the flask rinsed several times with deionized water and the rinses added to the filtrate. The toal volume of the filtrate was measured using and a 50.0 mL aliquot was removed for SEMs analysis. The NaOH traps were developed by adding 10 mL of a mixed diamine reagent and allowing the mixture to react for 30 minutes. The solution was quantitatively transferred to a 100 mL volumetric flask and brought to volume. Approximately 2 mL of solution was transferred to a cuvette and the absorbance at 670 nm was read using a spectrophotometer (Milton Roy Spectronic 601). To calibrate the AVS method, a standard sulfite solution was prepared by weighing 12 g of $Na_2S{\cdot}9H_20$ into 1.0 L of deionized water. The solution was standardized by the sodium thiosulfate titration procedure described in Allen *et al.* (1991) using a starch indicator. Absorbance was measured at 670 nm and used with solutions of known concentration to construct a standard curve. Simulaneously extracted metals were measured in the 50.0 mL aliquot removed from the sediment extract. The acid treatment removes metals which are weakly associated with the sediments and not incorporated in crystalline matrices. Samples were analyzed by ICP for the suite of metals described previously for that technique.

Grain Size and Total Organic Carbon Analysis: Grain size was measured using a sieving and pipette method as described in Plumb (1981). The mass of sediment used varied between 20 and 50 g of wet sediment depending on the texture (more for sandier sediments). Total organic carbon was determined by first weighing 10 mg of dried sample onto a pre-combusted glass fiber filter then analyzing with a Perkin Elmer 2400 Elemental Analyzer (950 ^{O}C combustion temperature). Cysteine was used as an external calibration standard.

Quality Controls for PAHs: To monitor for the efficiency of extraction and interferences that may be introduced in the sample preparation scheme, both spiked matrix samples and blanks were analyzed using both HPLC with fluorescence detection and GC-ITMS. A total of six spiked matrix samples were analyzed using NMFS sample 216. Amounts of each analyte

spiked along with the percent recovery were recorded. A standard reference material (SRM 1941; Organics in Marine Sediments) was obtained from the National Institute of Standards and Technology (NIST) to evaluate the efficiency of our extraction methods for removing PAHs from sediment. From 0.47 to 0.50 g dry weight of SRM 1941 was extracted seven times and analyzed. In general, PAHs analyzed by either method were within the NIST upper and lower confidence limits for the certified PAHs. The largest deviation from the NIST SRM material was for benzo(k)fluoranthene, which was 68% less than the stated NIST mean value when analyzed by GC-ITMS. Overall, the average deviation from the mean NIST SRM values (both certified and non-certified) was only 1% (some observations were biased high and some low) by either HPLC or GC-ITMS. The method detection limit (MDL) was determined as three times the standard deviation of repeated matrix spike determinations according to the Environmental Protection Agency protocol stated in the CFR (1991). A series of six blanks were also analyzed to check for contamination introduced during analysis.

Quality Control for Organochlorines and pesticides: Similar to the analysis of PAHs, both spiked sediments and a NIST SRM were analyzed for organochlorine compounds (NIST SRM 1941). Sediments were amended with 21 PCB congeners and 15 organochlorine pesticides or metabolites at three levels ranging from 1.2 ng to 5 ng total. The overall recovery (mean Å standard deviation) of organochlorines from amended sediments was 102 Å 23% for PCBs and 89 Å 32% for organochlorine pesticides plus metabolites. The results of the analysis of SRM 1941 are available from NOAA. The overall precision was not as good as for PAHs or metals and is evident by only three analytes falling between the NIST upper and lower confidence limits. In general, there is little apparent systematic bias in the deviation from the certified values (mean deviation = -1.6%).

Quality Control for Metals: Several precautions were taken to avoid contamination during metals analysis. Plastic containers and utensils were used wherever practical. All labware was washed thoroughly with soap and water, rinsed with tap water then three times with distilled water and then soaked in a 50% concentrated nitric acid bath. Following the cleaning procedure, the glassware was air dried and stored in covered plastic container. As a check for contamination, two types of blanks were analyzed. The first consisted of a 15% nitric acid solution and was used as the endpoint of the daily calibration curve. The second type was a solution that was processed using the extraction procedure to check for contamination that may arise during this process. A total of seven blanks of this type were analyzed. The limit of detection (LOD) was determined from the blank information as the mean blank plus three times the standard deviation. LODs ranged from 0.05 mg/kg for Cd by graphite

furnace AA to 390 mg/kg for Pb by ICP. To evaluate the efficiency of the nitric acid microwave digestion procedure, a standard reference material was analyzed seven times. Recoveries ranged from 64% recovery for Al to 175% recovery for Cd by ICP and averaged (mean Å standard deviation) 95% Å 25%. All reecoveries were within the acceptable confidence limits of the SRM material.

Quality Control for Acid Volatile Sulfide: To validate the AVS procedure, both and an intercalibration exercise with Skidaway Institute of Oceanography (SKIO) and spike recoveries were conducted. A total of 10 spiked blanks were analyzed during two recovery experiments. The first experiment consisted of five blanks spiked with 0.5, 1.0, 1.5, 2.0 and 2.5 mmoles of AVS and resulted in a recovery (mean Å standard deviation) of 85% Å 2.7%. The second recovery experiment consisted of five blanks spiked with 3.01 mmoles of AVS and resulted in a recovery of 87% Å 0.8%. The intercalibration exercise was the analysis by both NMFS-Charleston and SKIO of a field-collected sediment sample for AVS. The AVS measured in the sample were comparable with SKIO obtaining 2.64 Å 0.09 mmoles AVS (n=3) and NMFS-Charleston obtaining 2.08 Å 0.31 mmoles AVS (n=5). The results of the spike recoveries and the intercalibration exercises indicate that the AVS method used by NMFS-Charleston is reasonably precise and accurate.
Method limits of detection (MLODs) for these analyses are summarized in Appendix B. They generally corresponded with the target MLODs attained by other participants in the NS&T Program (Lauenstein and Cantillo, 1993). Chemical analyses were performed according to the quality control/quality assurance procedures of the NS&T Program, including instrument calibration, use of internal standards, replication of some analyses, percent recoveries of spiked blanks, and analyses of standard reference materials.

Statistical methods. Percent amphipod survival data from each station that had a mean survival less than that of the control was compared to the control using a one-way, un-paired t-test (alpha = 0.05) assuming unequal variance. Data were not transformed since an examination of data from previous tests have shown that *A. abdita* percentage survival data met the requirement for normality. A one-sample t-test was used to compare data from each sampling block with the mean performance control (CLIS) for each stratum.

Significant toxicity for *A. abdita* is defined here as survival statistically less than that in the performance control (alpha = 0.05). In addition, samples in which survival was significantly less than controls and less than 80% of control values were regarded as "highly toxic" or "numerically significant". The 80% criterion is used by EPA as a critical statistical value for *A. abdita* test data in EMAP-Estuaries methods (Holland, 1990). Similarly, the EPA/COE dredged material guidance manual (the "green book") also consider sediments toxic if survival relative to a reference sediment is less than 80% (U.S. EPA/U.S. ACOE, 1990). Furthermore, statistical power curves created

from SAIC's extensive testing database with *A. abdita* show that the power to detect a 20% difference from the control is 90%.

Microtox data were analyzed using the computer software package developed by the manufacturer to determine concentrations of the extract that inhibited luminescence by 50% (EC50). This value was then converted to mg dry wt. of sediment/mL of extract (where dry wt. was calculated as the weight of sediment after removal of porewater). To determine significant differences of samples from each station, pair-wise comparisons were made between contaminated samples and results from control sediments using three different analyses. Following an ANOVA test, a sequence of three increasingly conservative statistical tests were performed to determine significant differences from controls: Mann-Whitney, Dunnett's, and distribution-free. Dunnett's analyses were performed with log-transformed data.

For both the sea urchin fertilization and morphological development tests, statistical comparisons among treatments were made using ANOVA and Dunnett's one-tailed *t*-test (which controls the expriment-wise error rate) on the arcsine square root transformed data with the aid of SAS (SAS, 1989). The trimmed Spearman-Karber method (Hamilton et al., 1977) with Abbott's correction (Morgan, 1992) was used to calculate EC_{50} (50% effective concentration) values for dilution series tests. Prior to statistical analyses, the transformed data sets were screened for outliers (SAS, 1992). Outliers were detected by comparing the studentized residuals to a critical value from a t-distribution chosen using a Bonferroni-type adjustment. The adjustment is based on the number of observations (n) so that the overall probability of a type 1 error is at most 5%. The critical value (CV) is given by the following equation: $cv = t(df_{Error}, .05/(2 \times n))$. After omitting outliers but prior to further analyses, the transformed data sets were tested for normality and for homogeneity of variance using SAS/LAB Software (SAS, 1992).

Chemical data from the sample analyses were plotted on base maps to identify spatial patterns, if any, in concentrations. Trace metal concentrations were plotted against aluminum concentrations and compared to expected ratios for uncontaminated sediments developed by Schropp et al., 1988.

Similarly, the spatial patterns in toxicity were estimated by plotting data on base maps of each bay. Estimates of the spatial extent of toxicity were determined with cumulative distribution functions in which the toxicity results from each station were weighted to the dimensions (km^2) of the sampling stratum in which the samples were collected (Schimmel et al., 1994). The size of each stratum (km^2) was determined by use of a planimeter applied to navigation charts, upon which the boundaries of each stratum

were outlined. A critical value of less than 80% of control response was used in the calculations of the spatial extent of toxicity for all tests.

Chemistry/toxicity relationships were determined in a multi-step sequence similar that followed in previous studies (e.g., Long et al., 1994; 1995a; 1996) to ensure comparability. First, simple Spearman-rank correlations were determined for each toxicity test and each physical/chemical variable. The correlation coefficients and their statistical significance were recorded and compared among chemicals. Second, for those chemicals in which a significant correlation was observed, the data were examined in scatterplots to determine if there was a reasonable pattern of increasing toxicity with increasing chemical concentration and if any chemical in the toxic samples equalled or exceeded published numerical guidelines. Scatterplots were prepared with un-transformed bioassay data.

Chemical concentrations expressed in dry wt. were compared with the ERM values of Long et al. (1995b) developed for NOAA. Also, the concentrations of three PAHs (acenaphthene, fluoranthene, and phenanthrene) and two pesticides (dieldrin and endrin) expressed in units of organic carbon were compared to proposed National sediment quality criteria (SQCs) developed by U. S. EPA (1994). Finally, the concentrations of un-ionized ammonia were compared to LOEC concentrations determined for the sea urchin tests by the U. S. National Biological Service (Carr et al., 1996) and NOEC concentrations determined for amphipod survival tests published by Kohn et al. (1994). As a part of this step, trace metal:aluminum ratios were compared to those from reference areas in the southeastern U. S. (Schropp et al., 1990).

Third, the numbers of samples out of those that were analysed that exceeded the respective guidelines were determined. The combined results of these three steps were examined to determine which chemical(s), if any, may have contributed to the observed toxicity and which probably had a minor or no role in toxicity.

Correlations were determined for all the substances that were quantified in each bay, usually including total (bulk) trace metals, metalloids, trace metals simultaneously extracted (SEM) with acid volatile sulfides (AVS), un-ionized ammonia (UAN), percent fines, total organic carbon (toc), chlorinated organic hydrocarbons (COHs), and polynuclear aromatic hydrocarbons (PAHs). In addition, chemical indices calculated as the sums or averages of quotients formed by dividing the chemical concentrations in the samples by their respective ERM values (from Long et al., 1995b) were compared with measures of toxicity. Those substances that showed significant correlations were indicated with one, two, or three asterisks, depending upon the significance of the correlations. In correlation analyses involving a large number of variables, such as in this study, some correlations could appear to be significant by random chance alone. Adjustments often can be made to

account for this possibility. Note that in the results tables only those correlations shown with two or three asterisks would remain significant if the number of variables were taken into account in these analyses.

RESULTS

Toxicant Concentrations among Regions of the Study Area. Field notes taken from each sampling station are shown in Appendices A1-A3. Results of all toxicity tests and chemical analyses of the sediment samples are listed in Appendices B1-B3. Average, minimum, and maximum concentrations of selected substances were compared among six different regions (Table 1). The upper Savannah River included stations upstream of Fort Johnson and the lower Savannah River area included stations seaward of Fort Johnson.

Generally, the concentrations of most trace metals differed very little among the different regions of the study area (Table 1). For example, the concentrations of silver ranged from 0.12 to 0.48 throughout all areas and the average concentrations in the regions were very similar. The concentrations of chromium, lead and zinc, however, were slightly higher in Winyah Bay as compared to the other regions. The average concentrations of the five summed simultaneously-extracted trace metals (SEM: Cd, Cu, Ni, Pb, Zn) also differed relatively little among regions; some samples from Charleston Harbor, upper Savannah River, and Winyah Bay had relatively high concentrations. The average ratios of SEM concentrations to AVS concentrations were most elevated in the upper Savannah River and lowest in the Winyah Bay samples. Numerous samples in all regions had SEM/AVS ratios of less than 1.0, suggesting that trace metals were not highly bioavailable in most samples.

Average concentrations of major organic compounds were often highest in St. Simons Sound (Table 1). The average concentrations of total analyzed PAHs quantified with GC/MS were similar in St. Simons Sound and Charleston Harbor (approximately 2000 ng/g) and both areas had samples with unusually high concentrations. The concentrations of total DDTs (sum of DDTs plus metabolites) were relatively low and similar in all regions. One sample from St. Simons Sound had the effect of elevating the average concentration for that area. The average concentrations of total PCBs (double the sum of 20 congeners) were elevated considerably in St. Simons Sound, again as the result of one sample with extremely high PCB concentrations (1776 ng/g).

Toxicant Concentrations in Charleston Harbor. The concentrations of individual chemical substances and classes of chemicals are listed for each sample in Appendix B. In addition, these data are available in spreadsheet format from NOAA.

In the Charleston Harbor area, sediment texture differed considerably among stations (Figure 14). Samples collected in the lower harbor (stations C1-C4) were predominantly sand. Samples from the Ashley River were predominantly sand in the lower and upper stretches of the river and finer-

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grained silts and clays in the mid-river reaches. Texture also was heterogeneous in the Cooper River; some samples were primarily sand and others were mainly silts and clays. In the Wando River most samples were primarily sand. As expected, based upon the texture, the total organic carbon (toc) content varied considerably among stations (Figure 15). TOC content was relatively low (less than 1%) in most samples from the lower harbor, Wando River, lower Ashley River and a few scattered stations in the Cooper River. Most of the samples from the upper Ashley and Cooper river stations had 2-5% TOC. Aluminum concentration, an indicator of the presence of fine-grained particles, was highly variable among stations; showing a distributional pattern similar to that of TOC (Figure 16).

The concentrations of many potentially toxic substances followed distributional patterns similar to those of texture, TOC, and aluminum. For example, cadmium concentrations were lowest in the lower harbor, lower Ashley River, and Wando River and highest in the upper Ashley and Cooper rivers (Figure 18). Cadmium concentrations also were relatively high in Shipyard Creek (G stations). However, none of the cadmium concentrations equalled or exceeded the ERL value of Long et al. (1995b).

All of the other trace metals generally followed patterns similar to that of cadmium (Figure 19-27). Copper concentrations were highest in the upper Ashley and Cooper rivers, Shipyard Creek, and station CHP 10, however, only one sample (CHP 10) exceeded the ERL value for copper (Figure 19). A sample collected in upper Shipyard Creek had a very high chromium concentration, exceeding the ERL value for chromium (Figure 20). Several samples from the upper Ashley River exceeded the ERL value for lead (Figure 21). One sample from the Cooper River exceeded the ERM value for mercury (Figure 22). Nickel concentrations were relatively high in some samples from Shipyard Creek and the Cooper River (Figure 23). The highest concentrations of silver occurred in samples from the upper Ashley River and Shipyard Creek, however, none equalled the ERL value for silver (Figure 24). The Shipyard Creek stations also had relatively high concentrations of tin (Figure 25); no numerical guidelines have been derived for total tin. The concentrations of zinc were highest in samples from the upper Ashley River and Shipyard Creek, however, in all stations these concentrations were below the ERL value (Figure 26). The total concentrations of five divalent simultaneously-extracted metals (SEM) were highest in a few stations from the Ashley and Cooper rivers and Shipyard Creek, and as discussed later, most concentrations exceeded the respective acid-volatile sulfides (AVS) concentrations in the samples (Figure 27).

The concentrations of total PAHs were highest in station CHP 3 near downtown Charleston and several stations in the lower Ashley River (Figure 28). Some of the samples from the lower Ashley River with elevated PAH concentrations had petroleum-like sheens when collected. Total PAH

concentrations exceeded the ERL value, but were far below the ERM value for total PAHs (Figure 28). Total DDT concentrations were low relative to the ERL and ERM values and relatively uniform throughout the area (Figure 29). Similarly, the concentrations of total PCBs were relatively low in all stations except station H5-2 in the Cooper River in which the total PCB concentration (161 ppb) nearly equalled the ERM value of 180 ppb.

Based upon these chemical data, toxicity would be most expected in samples from the upper Ashley and Cooper rivers and Shipyard Creek and least likely in the Wando River, lower Ashley River and lower harbor where the sediments were primarily sandy with relatively low chemical concentrations. However, relative to applicable ERM values, most chemical concentrations were not very elevated and the higher TOC concentrations in these samples may minimize toxicity by inhibiting contaminant bioavailability.

Toxicant concentrations in Leadenwah Creek. Four samples from Leadenwah Creek were analyzed for chemical concentrations. At the uppermost station, the sediments were primarily sand and the concentrations of silt + clay increased down the estuary toward the confluence with the North Edisto River (Figure 31). Similarly, the concentrations of TOC increased down the estuary (Figure 32) from less than 1% to over 3%. The distribution of arsenic (Figure 33) exemplifies the patterns that were apparent for most substances, that is, concentrations gradually increased down the estuary with increasing fines and TOC concentrations. This overall pattern was evident with most trace metals and organic compounds (Appendix B). The concentrations of mercury increased sharply at the most seaward station (Figure 34). The concentrations of total PAHs also increased slightly from the upper to the lower regions of the estuary (Figure 35). In contrast the uppermost station had the highest concentration of total DDTs (Figure 36). Most substances occured in concentrations far below numerical guidelines; the exceptions being arsenic, mercury, and total DDTs which exceeded ERL values by slight amounts in a one or a few samples. None of the substances, however, exceeded respective ERM concentrations.

Toxicant concentrations in Winyah Bay. Chemical analyses were performed on all nine samples collected in Winyah Bay and both reference samples collected in North Inlet. Samples collected in the Georgetown Harbor and entrance channel were primarily silts and clays while the three samples from Winyah Bay had some sand (Figure 37). Percent sand decreased down the bay from station B5 to station B7. As expected the concentrations of aluminum also were high in the harbor stations and were relatively low in the bay stations (Figure 38). In following with the grain size, the TOC content was highest (3-5%) in the harbor stations and lowest in station B5 which had the lowest percent fines (Figure 39). Similarly, the concentrations of arsenic were highest in the inner harbor stations and lowest at the sandy sediments of station B5 (Figure 40); some concentrations exceeding the ERL value for

arsenic. Concentrations of cadmium paralleled those of arsenic; however, none of the concentrations equalled or exceeded the ERL value for arsenic (Figure 41). The spatial patterns for chromium, copper, and lead concentrations were similar to those of the other metals, closely following the distribution of fine-grained materials and TOC (Figures 42-44).

None of the concentrations of total DDTs were particularly elevated, although station B1-3 had a total DDT concentration in excess of the ERL value (Figure 45). Also, none of the samples had high total PCB concentrations, although, again, station B1-3 had the highest concentration of the nine samples. Similarly, the concentrations of total PAHs were highest in the sample from station B1-3; however, none of the concentrations equalled or exceeded the ERL value for total PAHs (Figure 47).

The two reference stations in North Inlet had consistently low toxicant concentrations, usually near or below detection or quantification limits. In two different samples the concentrations of fines were 15.2% and 45.4%; the concentrations of sands were 84.8% and 54.6%; and the concentrations of TOC were 0.7% and 1.8%. The concentrations of naturally-occurring trace metals, as expected, were higher in the sample with the highest concentrations of fines and aluminum. None of the toxicant concentrations measured would be expected to pose a toxicological risk.

Toxicant concentrations in Savannah River. With some exceptions scattered through the area, most stations in the upper Savannah River strata had primarily fine-grained sediments (Figure 48). Sediments in many of the B, G, and H strata were sticky clay with silt and some sands. A few stations in the C and B, however, were primarily sand with little or no silts and clays. In the lower sections of Savannah River, in contrast, many samples were primarily sand (Figure 49). Stations in the D and E strata often were sandy with minor amounts of fines. However, sediments from stations E3-5 and E3-9 had only small amounts of sand and were primarily clay. Six samples from strata A, the most inland stratum (not shown), had variable amounts of sand, silt, and clay in mixed sediments. Total organic carbon content ranged from less than 1% to nearly 8%. Most samples, however, had 2-4% TOC (Figures 50-51) with low concentrations in sandy samples and high concentrations in fine-grained samples. Station A2-4 (not shown) had an unusually high TOC content of nearly 8%

Cadmium concentrations were highest in samples collected directly adjacent to the city of Savannah (strata B3, B9) and in a Back River (station C-1) station, exceeding the ERL value for cadmium of 1.2 ug/g (Figure 52). The different concentration scale in the lower reaches of the river (Figure 53) reflect the considerably lower concentrations observed below Fort Johnson. Cadmium concentrations were very low (<0.35 ug/g) in strata A1 and A2 (not shown).

As observed with cadmium, the concentrations of zinc were highest near the city of Savannah (often >100 ug/g) and diminished considerably downstream (Figures 54-55). Note again that the scales in Figures 54 and 55 are different. All samples, including those from strata A1 and A2 (not shown), had zinc concentrations below the ERL value of 150 ug/g. Spatial patterns in the concentrations of other trace metals generally followed those observed with zinc and most elements equalled or exceeded their respective ERL values in a few samples; none exceeded the ERM values.

Detectable concentrations of total DDTs were observed primarily in stations in the upper reaches of the river. Station F2 (Dundee Canal) directly adjacent to the city of Savannah and station A1-2 in the upper river (not shown) had the highest concentration; otherwise, most stations had undetectable DDT concentrations (Figures 56-57). Total PCB concentrations also were highest in station F2, followed by station C3 in Back River (Figure 58), and diminished considerably downstream (Figure 59). Total PCB concentrations in all samples, including those from strata A1 and A2 were well below the ERL value for total PCBs (22.7 ng/g). Total PAH concentrations were low (<4022 ng/g, the ERL value) in nearly; all samples (Figures 60-61). The highest PAH concentrations occurred in samples from stations H1 and B2-4 in Stevens Terminal and the upper river, respectively (Figure 60). PAH concentrations were considerably lower in the lower reaches of the river than in the upper reaches.

Toxicant concentrations in St. Simons Sound. Chemical analyses were performed with all twenty samples collected in St. Simons Sound. Samples from most stations in the Turtle River (strata A, D, and E) and the lower Sound (stratum G) were sandy, while samples from the Brunswick Harbor (strata B and C) and upper Back River/Terry Creek (stratum F, station G1) were dominated by fine-grained materials (Figure 62). TOC content was relatively low (<2%) in most of the sandy stations and somewhat higher (>3%) in samples from stations with high percent silt and clay (Figure 63). Terry Creek and Brunswick Harbor stations had the highest TOC concentrations.

Compared to the other trace metals, the concentrations of chromium, lead and mercury, were elevated relative to ERL/ERM values. Brunswick Harbor samples (B and C strata) had the highest chromium concentrations (exceeding the ERL value of 81 ug/g) followed by those from Terry Creek (F stratum). All samples from the Turtle River, lower sound, and lower Back River had very low chromium concentrations (Figure 64). Lead concentrations were elevated above the ERL value (46.7 ug/g) only in stations from inner Brunswick Harbor (B stratum) and Terry Creek (F stratum); all other samples had very low lead concentrations (Figure 65). The distribution of elevated levels of mercury was further restricted to one station in Purvis Creek (P-1), two

stations in Terry Creek, and one Back River station (Figure 66). The ERL value for mercury (0.15 ug/g) was exceeded in these four samples.

The concentrations of both total DDTs and total PCBs were very high in the sample from station P-1 in Purvis Creek and relatively low in all other samples (Figures 67, 68). In the sample from station P-1, the total DDT concentration (15 ng/g) exceeded the ERL value (1.58 ng/g) by a considerable amount but was lower than the ERM value (46.1 ng/g). Most (12 ng/g) of the DDT was in the form of o,p'-DDD. In other stations (B1, B2, C1, and G1) with detectable amounts of DDT, this pesticide was primarily in the form of p,p'-DDD, p,p'-DDT, and p,p'-DDE. In the Purvis Creek sample the sum of 20 PCB congeners was 886.8 ng/g, equivalent to a total PCB concentration of 1774 ng/g. This concentration is well above the ERM value of 180 ng/g. The PCB at this station was primarily in the form of 9- and 10-chlorine congeners (Appendix B). Total PCB concentrations in samples from stations A3 and B1 also exceeded the ERM value for total PCBs.

Samples from three stations (B1, B2, and F2) exceeded the ERL value for total PAHs (Figure 69); all other stations had relatively low PAH concentrations. The PAHs in these three samples were primarily high molecular weight (4- and 5-ring) compounds, notably pyrene, fluoranthene, and benzo fluoranthene (Appendix B).

Incidence of Toxicity among Regions. All tests were performed according to widely-accepted protocols. Tests of both negative (non-toxic) controls and positive (pollutant) controls were within acceptable limits.

In the amphipod tests all measures of dissolved oxygen, temperature, salinity, and pH showed the tests were run within acceptable limits for *Ampelisca abdita*. Un-ionized ammonia concentrations were below levels known to cause toxicity. In the 1993 tests of samples from Charleston Harbor/Winyah Bay/Leadenwah Creek performed by NBS, the tests of SDS in water showed 96-h LC50s of 13.76 mg SDS/L (95% confidence limits of 13.24-14.29 mg/L) in the first experiment and 14.73 mg SDS/L (95% confidence limits of 13.64-15.90 mg/L). During year 2 the LC50 values calculated by SAIC ranged from 5.27 mg SDS/L to 11.22 mg SDS/L (no confidence limits calculated). These data suggested that the amphipods from New England were slightly more sensitive than those from San Francisco Bay. Both results are acceptable.

Survival ranged from 85-89% in San Francisco Bay reference sediments in the amphipod tests in the 1993 tests. In the 1994 tests of St. Simons Sound/Savannah River samples performed by SAIC, control (central Long Island Sound) survival ranged from 76-98% in eleven experiments. Samples in which control survival dropped below acceptable levels (85%) were re-tested with control survivals increasing to 92% and 98% in the re-tests. The 1994 tests of the positive controls showed LC50s ranging from 5.27 to 11.22 mg

SDS/L, suggesting somewhat higher sensitivity among east coast amphipods compared to those from the west coast.

In the 1993 urchin fertilization tests, porewater dissolved oxygen ranged from 78 to 104% saturation and all sulfide concentrations were below detection (0.01 mg/L) Values for pH ranged from 7.04 to 8.31. The concentrations of ammonia ranged from 1.2 to 249.0 ug/ L and averaged 54.3 ug/ L, well below toxicity threshold (LOEC) of 800 ug/ L established by NBS. Percent fertilization success in the Redfish Bay, Texas control was 97.4% in 100% porewater. In the North Inlet reference sample fertilization success was 97.6% in 100% porewater. Similarly, in the 1994 tests dissolved oxygen concentrations ranged from 86 to 128% saturation and sulfide concentrations were not detectable. Values for pH ranged from 6.97 to 8.67. Un-ionized ammonia concentrations ranged from 4.1 to 1263 ug/l, exceeding the toxicity threshold in only one sample (B2-3 in the upper Savannah River).

In the Microtox tests performed by NMFS results from reference toxicant (phenol) tests showed EC50 values ranging from 19.98 to 32.83%, averaging 24.78%. Similarly, tests of DMSO blanks showed no toxicity for each of the tests. Tests of the North Inlet reference sediment showed EC50s of 1.46, 3.02,0.84, 0.82, and 0.77 mg/ml, indicating a relatively consistent response among test batches.

Summarized results of the toxicity tests are listed in Table 2 for Charleston Harbor, Winyah Bay, and Leadenwah Creek. The numerical results are accompanied by indications of statistical significance: "ns" for non-toxic ($p>0.05$); a single asterisk for statistical significance ($p<0.05$ only); and a double asterisk for highly significant ($p<0.05$ and >20% difference from control). In the Microtox tests, three asterisks were shown when results were significant in Mann-Whitney, Dunnett's, and distribution-free analyses. Also, a "toxicity tally" is shown which is the summation of the levels of significance observed in each toxicity test, i.e. the number of asterisks assigned to each result. The mean ERM quotients, indicators of the overall degree of chemical contamination for the samples, are listed for those samples analyzed for chemical concentrations. This index was based upon the average of 25 chemical concentrations divided by their 25 respective ERM values (from Long et al., 1995).

None of the samples from Charleston Harbor and vicinity caused a significant decrease in amphipod survival relative to the controls (Table 2). In contrast both the Microtox bioluminescence and sea urchin fertilization tests indicated toxicity in numerous samples. In some samples, such as those from stations B5-1 and B6-2 in Winyah Bay, these two bioassays showed good consensus regarding the toxicity of the samples (toxicity tallies of 9 and 8, respectively). In most of the samples that were toxic in the Microtox tests, they also were toxic in the urchin fertilization tests, but these two tests did not show good

agreement in many other samples. Only two samples from Leadenwah Creek were toxic in any of the tests and the test results were only slightly different from the controls. There was a much wider range in response among the Winyah Bay samples: one sample was non-toxic in all tests and two others showed very high toxicity. The sample from station B4-1 was unusually toxic and also had a relatively high mean ERM quotient (0.147).

Two samples from the Ashley River had the highest mean ERM quotients (>0.2), indicating the highest concentrations of mixtures of substances; however, neither of these samples was very toxic. However, most of the samples from the Ashley River were toxic in at least one of the bioassays, especially those performed with sea urchins. In the Cooper River, all except the sample from station H1-1 were slightly to moderately toxic, as indicated by toxicity tallies of 0 to 4, and most had low to moderate chemical concentrations (mean ERM quotients of 0.01 to 0.18). The six samples from the lower Wando River had similarly low to moderate toxicity and chemical concentrations. Among the eleven samples tested for the Charleston Harbor Project, five had moderate to high toxicity (toxicity tallies of 6-8), and all had low to moderate chemical concentrations (mean ERM quotients of 0.01 to 0.17) similar to those collected elsewhere in Charleston Harbor.

Responses in the cytochrome P-450 RGS bioassays performed on selected samples from Charleston Harbor and Winyah Bay ranged from 1.8 to 86.3 ug/g benzo(a)pyrene equivalents (Table 3). Induction was considerably higher in the samples from the Ashley River (D strata) than in those from the Cooper River (H strata). Induction was highest in two adjacent samples (D3-3 and D4-1) from the Ashley River and in a sample (G2-1) from Shipyard Creek; intermediate in several samples from upper Winyah Bay and the Ashley and Cooper rivers; and lowest in several samples from the lower reaches of Winyah Bay.

In the meiobenthic copepod bioassays of reproduction, copepodite stage production and naupliar stage production were significantly reduced in one sample collected at station CHP 4 (Table 3). However, total copepodite+naupliar production was not significantly reduced. Clutch size was significantly reduced in one sample from Leadenwah Creek and seven samples from Charleston Harbor; responses ranged from 8.8 to 100.7.

Toxicity and chemistry data for the Savannah River are summarized in Table 4. The sample from station A1-1 was extremely toxic in the amphipod test, but non-toxic in all other tests and it had very low chemical concentrations. Three other samples from strata A1 and A2 in the upper-most stretch of the study area were toxic in the amphipod tests, two were toxic in the Microtox tests, and only one was toxic in the sea urchin development test of 100% porewater. In the B strata adjacent to downtown Savannah, results of the toxicity tests showed a wide range in response; toxicity tallies ranged from 0 to

12. Toxicity tallies were 10-12 in seven of the samples. However, the mean ERM quotients indicated slight to moderate chemical concentrations (ranging from 0.01 to 0.14). One sample each from the Back River and lower Savannah River strata was toxic in amphipod tests and none from the south channel was toxic in that test. One sample from the lower Savannah River and three samples from the three Savannah harbor strata were toxic in Microtox, urchin fertilization, and urchin development tests (toxicity tallies of 10-11). All seven samples from the Savannah harbors had similar chemical concentrations (mean ERM quotients of 0.09 - 0.14).

In the St. Simons Sound study area, two samples (both from Terry Creek) were toxic in the amphipod tests (Table 5). Amphipod survival was 0.0% in the sample from station F2-1, a very unusual result for this relatively resistant test. Also, the chemical concentrations were relatively high in this sample (mean ERM quotient of 0.22). Elsewhere in this estuary, two samples from the Brunswick Harbor/East River area showed relatively high toxicity (toxicity tallies of 10). The sample from station C2-1 was toxic in Microtox, urchin fertilization, and urchin development tests. Another sample from this region (station B2-1) had relatively high chemical concentrations (mean ERM quotient of 0.31). The sample from the Purvis Creek stratum was the most contaminated (mean ERM quotient of 0.47), but it was not toxic in any of the tests. Overall, the highest chemical concentrations observed in the entire study area were encountered in samples from stations B2-1 and P1 in the St. Simons Sound estuary.

The incidence of test results that were statistically significant ($p<0.05$) is summarized in Table 6. Data from the copepod reproduction and urchin embryo development tests are not included since they were not performed with all samples. Toxicity was most prevalent among the Winyah Bay samples in which 6 of 9 and 8 of 9 samples were toxic in the tests performed with Microtox and urchin fertilization in 100% porewater, respectively. Among all 45 tests performed with Winyah Bay samples, a total of 21 (46.7%) results showed significant differences from controls. Many of the samples from Charleston Harbor were significantly toxic, especially in the Microtox and urchin fertilization tests, the two most sensitive assays. In Charleston Harbor, a total of 97 (30%) test results of 325 bioassays performed showed significant differences from controls. Much smaller proportions of samples from the Savannah River and St. Simons Sound were toxic (21% and 12%, respectively). Ten of the samples from the Savannah River were toxic in the least sensitive test, the amphipod survival bioassay. The relatively high incidence of toxicity in the urchin fertilization tests performed with 100% Savannah River porewater diminished markedly with dilution of the samples - none of the samples were toxic in tests of 25% porewater. Finally, the samples from Leadenwah Creek had the lowest incidence of toxicity; none of the samples was toxic in the amphipod survival or urchin fertilization

tests performed with either 100% or 50% porewater. Unexpectedly, however, two samples were toxic in tests of 25% porewater.

Spatial distribution of toxicity in Charleston Harbor. None of the 65 samples collected in Charleston Harbor and North Inlet from either the NOAA stations or the Charleston Harbor Project stations were toxic ($p>0.05$) in the amphipod tests. Therefore, no distributional map is provided.

Microtox test results were analyzed with three statistical analyses, representing increasing levels of conservativeness: Mann-Whitney, Dunnett's, and distribution-free. Samples in which average results were not significantly different from the North Inlet reference samples in the least conservative analysis (Mann-Whitney) are shown as open circles in Figure 70. Those determined to be significantly different from the reference samples in the three statistical analyses are shown with different symbols. In Charleston Harbor none of the samples was significant in the distribution-free analysis. However, test results for the samples from stations CHP 10 in the Wando River, CHP -3 and E2-1 in Charleston Harbor, H1-1 and H7-1 in the lower Cooper River, and CHP 7 and D3-1 in the Ashley River were significant in both the Mann-Whitney and Dunnett's analyses. In addition, eight of the samples from the Cooper River showed significant results in only the Mann-Whitney analyses. Only one of the samples from the lower Ashley River and lower harbor were toxic in this test.

The sea urchin fertilization tests were performed in three porewater concentrations (100%, 50%, and 25%) and test results for each dilution were compared with those from the controls to determine significant differences (Figure 71). Samples with the highest toxicity were those that cause significant results in all three porewater concentrations. Toxicity in the 100% porewater tests was pervasive throughout Charleston Harbor; at least some samples collected in all three rivers were toxic to urchin fertilization. Many of the most toxic samples came from the lower Ashley River and the region of the lower harbor that receives the Ashley River. Most samples from Shipyard Creek (G stations) and the lower Cooper River in the vicinity of Shipyard Creek caused toxicity in 50% or 25% porewater tests. The most seaward stations, C1 and C2, were not toxic in these tests.

Cytochrome P-450 RGS assays were performed on selected Charleston Harbor and Winyah Bay samples. Data are shown the 20 Charleston Harbor samples as benzo(a)pyrene equivalents (ug/g) of fold-inducing substances in solvent extracts of the sediments. In Charleston Harbor, most of the samples tested were from the Ashley River where petroleum-like sheens were often observed in the samples. Station B5-2 from lower Winyah Bay (not shown) produced a baseline level of response (2 ug B(a)P equivalents/g), comparable to responses at other clean sites. Sediments from two Ashley River stations (D3 and D4) and one Shipyard Creek station (G2) produced the highest levels

of induction (70-86 ug/g) in this assay. Sediments with levels of B[a]PEq above ug/g exhibited degraded benthic communities in a survey of sediment quality in San Diego Bay (Fairey et al., 1996). Stations in the upper Cooper River and lower Winyah Bay provided the lowest responses in these tests.

Twelve samples were tested for adult survival and reproductive success among meiobenthic copepods (Figure 73). None of the survival rates were significantly lower than North Inlet reference samples. Only three reproductive end-points showed significant results relative to reference samples: naupliar production, copepodite production, and clutch size. Clutch size was significantly depressed in sediments from seven stations, including all samples from the lower Ashley River and all except one of the samples from the lower harbor/Charleston Harbor. Sediment from station CHP 4 near the mouth of the Ashley River caused significant responses in all three end-points.

In summary there were many samples from Charleston Harbor that were toxic in one or more of the bioassays; however, none were toxic in the least sensitive bioassay performed - the amphipod survival test. Samples indicated as toxic in one or more tests were scattered throughout the study area. No single region was remarkably toxic in all tests and there was relatively little concordance among the tests. These data suggest, therefore, that toxic samples were scattered throughout the area, not concentrated in any particular area, and, as judged by the amphipod tests, toxicity was not severe. The Microtox tests indicated many samples from the Cooper River were toxic and only two samples were toxic from the Ashley River, whereas the urchin fertilization and copepod reproduction tests indicated that most Ashley River samples were toxic. However, both the Microtox and urchin fertilization tests showed toxicity in some of the same stations; notably, CHP 7, CHP 10, D3-1, G1, H5-4, H8-1, and H6-1. The station most toxic to copepod reproduction, CHP 4, was also toxic in the urchin fertilization test, but not in the Microtox test. Several of the most seaward stations in the lower harbor were consistently non-toxic in the tests performed, suggesting that toxic conditions did not extend beyond the harbor entrance.

Spatial distribution of toxicity in Leadenwah Creek. None of the 9 samples collected in Leadenwah Creek were toxic in the amphipod tests. Therefore, no distributional map is provided. Cytochrome P-450 assays were not performed on Leadenwah Creek samples. Copepod reproduction tests were performed on one sample from Leadenwah Creek, station A1-8, and significantly reduced clutch size was observed in that sample.

Results of the Microtox tests are summarized in Figure 74. The sample from one station, A1-1, in the upper reaches of the creek showed significant results in both the Mann-Whitney and Dunnett's analyses. In the urchin fertilization tests, none of the samples of 100% porewater or 50% porewater

were toxic. However, two samples both from upper reaches of the creek showed slight toxicity in the tests of 25% porewater only (Figure 75).

In summary the samples from Leadenwah Creek, a system that has historically received considerable pesticide runoff from agriculture, were not highly toxic. Only one sample showed toxicity in the Microtox tests, none were toxic in the amphipod survival tests, and a very slight decrease in urchin fertilization was observed in the porewaters of two samples.

Spatial distribution of toxicity in Winyah Bay. None of the nine samples collected in Winyah Bay were toxic in the amphipod survival tests. Copepod reproduction tests were performed on one sample (station B 3-1) from the lower Sampit River and no significant effects were observed.

In the Microtox tests, six of the nine samples were significantly different from controls in at least the Mann-Whitney analysis (Figure 76). Samples from stations B1-3 and B1-2 in the Georgetown harbor area, B4-1 in the lower Sampit River, and B5-1 in the upper Winyah Bay were the most toxic. A similar pattern was observed with the results of the urchin fertilization tests (Figure 77). The sample from station B3-1 was not toxic and the samples from stations B1-2, B4-1 and B5-1 were the most toxic. The remaining samples were toxic only in the tests of 100% porewater.

In the cytochrome P-450 RGS assays, fold induction was low in the sample from station B3-1 which was not toxic in the Microtox and urchin fertilization tests (Figure 78). However, fold induction also was very low in the samples from stations B4-1 and B5-1 which were toxic in the other bioassays. Assay results were highest in stations B1-3 and B7-1.

In summary eight of the nine samples from Winyah Bay showed toxicity in at least one of the bioassays and toxicity was most severe in the Georgetown harbor area. Toxicity generally decreased seaward down the bay, however, the most seaward station was toxic in two tests and showed the highest fold induction rate in the cytochrome P-450 assay. Therefore, the seaward extent of toxicity was not determined.

Spatial distribution of toxicity in St. Simons Sound. In amphipod survival tests two of the 20 samples from St. Simons Sound were significantly different from controls (Figure 79). Both samples (from stations F1-1 and F2-1) were collected in Terry Creek, a tributary to the Back River northeast of the city of Brunswick. The remaining 18 samples tested were not toxic in this test. Similarly, the Microtox tests indicated that samples from stations F1-1 and F2-1 were highly toxic (Figure 80). In addition, samples from station C2-1, E2-2, and G1-1 were highly toxic in this test. As in the amphipod tests, samples from the Turtle River and St. Simons Sound were not toxic in the Microtox tests.

The urchin embryological development tests also indicated that samples from stations F1-1 and F2-1 were toxic (Figure 81). However, in this test four of the samples (B1-1, C1-1, C2-1, and C3-1) from the Brunswick harbor were the most toxic, with significant effects at all three porewater concentrations. Some samples from the Turtle River were toxic in tests of 100% or 50% porewater, but toxicity diminished downstream and samples from lower St. Simons Sound were not toxic in this test.

In contrast to the results of the other tests, the urchin fertilization test did not indicate that samples from stations F1-1 and F2-1 were toxic (Figure 82). However, as indicated in the urchin embryological development tests, most samples from the Brunswick harbor were toxic. Also, two samples from the upper reaches of the Turtle River were toxic. None of the samples from the lower Turtle River, lower Back River, or lower St. Simons Sound were toxic in this test.

In summary toxicity was most severe in the two samples collected in Terry Creek; all except the urchin fertilization tests showed relatively severe toxicity there; and average amphipod survival was 0.0% in one of the samples. Samples from the Brunswick harbor area were toxic in several bioassays, notably the urchin tests. Samples from some stations in the Turtle River were toxic in only the urchin tests. The samples from the lower reaches of the Turtle River and St. Simons Sound were consistently non-toxic, indicating, as in Charleston Harbor, that toxic conditions did not extent beyond the entrance to the estuary.

Spatial distribution of toxicity in upper Savannah River. In amphipod survival tests only five samples were significantly different from LIS controls; three samples from the uppermost reach (stratum A) of the river upstream of the city of Savannah and one sample from Back River (station C-1) below the city of Savannah (Figure 83). Mean amphipod survival in the sample from station A1-1 was 4.0% of the control, an unusual result for this test. All other samples were non-toxic in this test.

In the Microtox tests considerably more samples were different from controls than in the amphipod tests, including many samples collected near the city of Savannah (Figure 84). Of the 43 samples tested, 23 were toxic as determined with Mann-Whitney analysis. Toxicity in this test was most severe among samples taken in strata B4, B5, B7, B9, and H and least severe among the samples from strata B1 and B8. Two of samples from the upper most reaches of the river - strata A1 and A2 - were toxic.

Similar to the Microtox tests, the urchin embryological development bioassays showed a high incidence of toxicity in this area (Figure 85). In these tests 31 of 43 samples were significantly different from controls in at least

100% porewater. Samples with the most severe toxicity were collected from strata B2, B3, B5, B9, G and H. Many of the samples from the uppermost reaches of the river (strata A1, A2 and B1) were among the least toxic.

In the urchin fertilization tests, 18 of 43 samples were toxic in at least 100% porewater (Figure 86). Samples showing highest toxicity were clustered around the middle of the region within strata B3, B9, and F. Many of the samples from this central cluster also were toxic in the embryological development bioassays. Most of the samples from the upper reaches of the river and from the downstream strata were non-toxic.

In summary stations in which toxicity was observed were scattered throughout the region and each bioassay showed somewhat different patterns in toxicity. However, three tests - the Microtox tests and both urchin tests - indicated that samples from the central portion of the region were toxic. Specifically, all except two samples collected within strata B3, B4, B9 and F were toxic in these three tests. With some major exceptions, most samples collected upstream of the city of Savannah were non-toxic in these three tests. Also, there was generally less toxicity downstream of the city and in Back River. Data from the amphipod survival tests, the least sensitive bioassay performed, showed a different pattern in toxicity; the only toxic stations were those from the upper reaches of the river and from Back River.

Spatial distribution of toxicity in lower Savannah River. Seventeen samples were collected below Fort Johnson. In amphipod survival tests only one sample (from station D3,1-4) was toxic (Figure 87). This sample was collected far a location downstream of the city of Savannah where most pollutant sources would be expected.

In the Microtox tests, the sample from station D3,1-4 was not toxic; however, several other samples collected downstream were toxic (Figure 88). Toxicity was most severe in samples from station D3,3-2, station E3,5, and station E3,9. Samples from strata E1, E2, and D2 were among the least toxic. Toxicity did not disappear at the most seaward stations near the mouth of the river, suggesting that the seaward extent of toxicity was not encountered.

Samples from three stations - D1,3-1 and E3,5 and D3,3-2 - which were toxic in the Microtox tests also were highly toxic in the urchin embryological development bioassays (Figure 89). Many of the stations within strata D2, E1 and E2 that were non-toxic in the Microtox tests also were non-toxic in this test. As in the amphipod tests, only one sample was toxic in the urchin fertilization tests (Figure 90). In this case, however, the toxic sample was collected from station D1, 3-1 near Elbe Island. Station D1,3-1 was toxic in both urchin tests and in the Microtox tests.

In summary, toxicity was scattered among the stations and no clear spatial pattern in toxicity was evident. Two samples - one from the upper reach of this region and another collected near the mouth of the river - showed toxicity in three of the four tests. Overall, based upon the results of all tests, the samples from the lower Savannah River/south channel stations were considerably less toxic than those from the upper Savannah River.

Concordance Among Toxicity Tests. Spearman-rank correlations were calculated to estimate the degree of concordance among the different toxicity tests. Concordance was determined for each region (Charleston Harbor and vicinity, Savannah River, St. Simons Sound) and for the entire study area. Positive correlation coefficients (Table 7) indicated the results of the tests shown similar spatial trends in toxicity, whereas negative coefficients indicated different patterns.

In Charleston Harbor, the only significant positive correlation was between results of the Microtox and urchin fertilization tests (Rho = +0.389, $p<0.001$). All of the remaining correlations were non-significant. In the Savannah River samples, the strongest positive correlation was, as expected, between urchin fertilization and urchin development. Also, the results of the Microtox tests were correlated with both urchin tests. In contrast amphipod test results showed negative correlations with both of the urchin tests. Similarly, in St. Simons Sound results of the Microtox tests were positively correlated with urchin fertilization, whereas amphipod survival was negatively correlated with urchin fertilization. As in the Savannah River urchin fertilization and development were strongly correlated with each other in the St. Simons Sound samples.

When the results of these tests from all regions were combined, the patterns observed in Savannah River and St. Simons were also apparent. Urchin fertilization and development were strongly correlated with each other; both urchin tests were positively correlated with Microtox results; and both urchin tests were negatively correlated with amphipod survival. These results suggest that the results of both urchin tests and the Microtox tests followed overlapping and similar, but not duplicative, patterns whereas a different spatial pattern in toxicity was indicated in the amphipod survival tests.

Spatial Extent of Toxicity. The spatial extent of toxicity was estimated for each estuary based upon toxicity test data from the three bioassays (urchin fertilization, amphipod survival, Microtox) that were performed throughout the entire area (Table 8). The critical value used in these calculations was <80% of controls; that is samples in which test results were less than the critical value were assigned to the "toxic" category. The sizes of the strata weighted to the number of samples within the stratum that were "toxic" were summed to provide an overall estimate for each estuary. Also, the estimates for each estuary were summed for the entire study area.

The total study area encompassed approximately 88 km^2, including 41 km^2 in Charleston Harbor, the largest estuary studied (Table 8). In the amphipod survival tests "toxic" samples as defined by the critical value were observed only in samples from the Savannah River and St. Simons Sound. The spatial extent of toxicity in amphipod survival tests in these two estuaries was approximately 0.2 and 0.1 km^2, equivalent to 0.3% of the total study area. In the urchin fertilization tests the spatial extent of toxicity was approximately 18.7 km^2 (21.3% of the total area), most of which (12.5 km^2) occurred in Charleston Harbor. In Winyah Bay toxic samples in the urchin fertilization tests represented about 3.1 km^2 (42.2% of this small estuary).

The estimated spatial extent of toxicity was highest in the Microtox tests (48% of the total area, Table 8). In these tests toxicity was most pervasive in Winyah Bay and Savannah River, 70% and 57% of these areas, respectively. Approximately 43% and 46% of Charleston Harbor and St. Simons Sound,respectively, were toxic in these tests. Only one sample, representing 20% of the area, was toxic from Leadenwah Creek.

Correlations between Toxicity and Chemical Concentrations. Simple, Spearman-rank correlations between measures of toxicity and the concentrations of chemical substances in the samples were determined to identify and quantify concordance. Correlations were determined for the 66 samples from Charleston Harbor/Winyah Bay/Leadenwah Creek, 61 samples from Savannah River, and 20 samples from St. Simons Sound in which chemical concentrations were determined (Appendices B1-B3). Correlations do not identify or imply cause-effect relationships; rather, they simply identify the degree, if any, of concordance between independent variables (chemistry) and dependent variables (toxicity) in the same samples. Correlations were determined for individual chemicals and classes of chemicals. In addition, correlations were determined with several cumulative chemical indices, which were calculated by dividing concentrations by their respective ERM values (Long et al., 1995) and summing the quotients.

Correlations were expressed as coefficients (rho, corrected for ties) with either a positive or negative sign. A negative sign would suggest that, for example, survival decreased as a chemical concentration increased. Correlations were identified as non-significant (ns, $p>0.05$), significant ($p<0.05$*, $p<0.001$**, or $p<0.0001$***). However, correlations performed with a sufficiently large number of variables can be significant by random chance alone. In these analyses correlations identified as ** ($p<0.001$) and *** ($p<0.0001$) would remain significant if the number of variables were taken into account, whereas those identified as * ($p<0.05$) would not remain significant.

In Charleston Harbor and vicinity (including North Inlet, Winyah Bay, and Leadenwah Creek) 66 samples were tested for toxicity and analyzed for

chemical substances (Table 9). None of the samples tested for amphipod survival showed significant effects. Therefore, with no significant gradient in response, none of the correlations with chemical substances were significant. All of the coefficients listed in Table 8 had positive signs except for those with un-ionized ammonia and results of the P-450 RGS assays.

In contrast to the amphipod tests, the microbial bioluminescence (Microtox) tests showed significant correlations with many different substances in Chareston Harbor and vicinity (Table 9). The large number of significant correlations indicated that many substances were correlated with each other. Among the trace metals, all except silver, cadmium, and mercury showed significant negative correlations with bioluminescence. The concentrations of copper showed the strongest correlations among the trace metals. However, the ratios between total SEM concentrations and AVS concentrations were positively correlated with bioluminescence, suggesting light production increased with increasing metals concentrations normalized to respective AVS concentrations. Bioluminescence significantly decreased with increasing percent fines and percent total organic carbon, indicating fine-grained sediments had the highest toxicity, probably due to the presence of the highest chemical concentrations. With negative correlation coefficients of 0.26 to 0.35, all classes of organic compounds were similarly correlated with Microtox test results. Again, these data suggest that organic compounds co-varied with each other in mixtures.

Microtox test results were significantly correlated with all chemical concentration/ERM ratios in Charleston Harbor (Table 9), including those for all 25 substances for which an ERM was prepared (Long et al., 1995b). These data, again, suggest that bioluminescence decreased as the concentrations of mixtures of substances normalized to their respective ERM values increased. Furthermore, the correlations among all classes of organics (total PAH, total PCBs, total DDTs, total pesticides) were significant. For example, the concentrations of total PAH and total PCB were highly correlated ($rho = 0.661$, $p<0.0001$). Similarly, total PCBs and total pesticides ($rho = 0.492$, $p<0.0001$) and total PCBs and total DDTs ($rho = 0.485$, $p<0.0001$) were highly correlated with each other. Consistent with the correlations for individual trace metals, the correlation between bioluminescence and the sum of the 9 trace metals/ERM quotients was strongest.

Correlations between urchin fertilization and chemical concentrations in the Charleston Harbor samples were significant only for silver and the sums of total PAHs, total PCB congeners, and sums of non-DDT pesticides (Table 9). The correlation with silver was strongest but would not remain so if the number of variables were taken into account.

Cytochrome P-450 RGS bioassays were performed on solvent extracts of 29 of the Charleston Harbor and Winyah Bay samples. These tests have been

shown in laboratory trials to respond to a number of different mixed-function oxidase inducing chemicals, notably dioxins, and to a lesser extent PAHs and some PCB congeners. Among the 29 samples chosen from Charleston, there was a wide range in response (2 to 86 ug/g) in the test results. As expected, none of the correlations were significant with any trace metals. However, test results correlated very strongly with the concentrations of a number of organic substances that would be expected to induce responses (Table 9). Spearman-rank correlations were highest for the high-molecular weight PAHs and PCBs, whether or not they were normalized to the ERM concentrations. These data suggest that, as expected, the P-450 results co-varied with complex mixtures of many different organic substances in the sediments. The 4- and 6-ring PAHs, which are the primary compounds associated with the Ah-receptor, would be particularly important in triggering these bioassay responses.

A series of copepod reproduction bioassays was performed with 19 of the Charleston Harbor samples. Total copepodite/naupliar production and total clutch size were not significantly correlated with any of the measured chemicals in the samples. A few trace metals indicated weak correlation coefficients, but none were significant (Spearman-rank, $p<0.05$, $n = 19$), especially if the numbers of variables were accounted for.

In the Savannah River, matching toxicity and chemistry data were developed for 61 samples (Table 10). As observed in Charleston Harbor and vicinity, none of the substances measured showed a significant negative correlation with amphipod survival, largely due to the relativley low sensitivity of this bioassay. Chemical concentrations in the station in which amphipod survival was 0.0% were not very high. Only the concentrations of cadmium, total SEM and the SEM:AVS ratios were significantly correlated with Microtox test results.

In sharp contrast to the amphipod and Microtox test results, both of the urchin tests performed on Savannah River samples showed strong negative correlations with many different substances (Table 10). These correlations were particularly strong for ammonia, zinc, total SEM, total metals/ERM quotients, total PAHs, and total high molecular weight PAHs. Among the highest correlations was that with sum of the 24 chemicals/ERMs quotients. The highly significant correlations with sums of chemical concentrations normalized to respective ERM values suggested that, as observed in Charleston Harbor, bioassay results co-varied with mixtures of numerous substances. Furthermore, the correlations between all classes of organic compounds (PAHs, PCBs, DDTs, pesticides) were highly significant (rho = 0.40 to 0.69, $p<0.001$ or $p<0.0001$).

In St. Simons Sound matching toxicity and chemistry data were available for 20 samples (Table 11). Results of Microtox tests were highly correlated with

aluminum, iron, and nickel none of which are highly toxic substances. Test results also were correlated with the sum of 5 SEM concentrations, but not with the SEM:AVS ratios. Relatively strong associations were apparent between microbial bioluminescence and both the concentrations of PAHs and the sums of the 24 concentrations/ERMs quotients. Results of the urchin fertilization tests were highly correlated with many trace metals concentrations, but not with the concentrations of PCBs, DDTs, and pesticides. Urchin embryological development was correlated with many of these same substances, but the coefficients and significance of the correlations were weaker than seen with the fertilization tests. In both bioassays the concentrations of un-ionized ammonia were associated with test results.

Toxicity and chemistry data from all 147 samples were compiled to determine if any correlations with classes of substances observed in individual regions remained significant over the entire study area (Table 12). Correlations were determined only for summed chemical classes. Many correlations remained significant and some strengthened in this combined data set. The correlations between ammonia and both urchin tests were highly significant. Also, there was a very strong association between the cumulative ERM quotients and toxicity in the Microtox and both urchin tests. As noted above in each individual region, it was apparent that mixtures of substances co-varying with each other were strongly associated with toxicity in these three bioassays.

Comparisons of Trace Metals Concentrations to Reference. Trace metals concentrations in sedments collected from reference areas in the southeastern USA have been observed to co-vary with average grain size in the sediments, which, in turn, co-varies with aluminum content (Schropp et al., 1990; Schropp and Windom, 1988; Windom et al., 1989). By comparing trace metals concentrations to aluminum concentrations in clean samples, these investigators determined the metals-to-aluminum ratios to be expected in clean reference areas and the 95% confidence limits of these ratios. Exceedances of the upper 95% confidence limits are assumed, by this technique, to represent polluted conditions in which there was an excess of a trace metal.

Trace metals analyses in this survey were performed with nitric acid digestions, which would be expected to extract less of the clay-bound aluminum in the sediments than in hydrofluoric acid digestions. The metals-aluminum ratio tool is based upon total (hydrofluoric acid) digestions (Schropp et al., 1990). Therefore, the following metals-aluminum plots may exaggerate the concentrations of metals relative to the concentrations of aluminum (perhaps by a factor of roughly two).

Figures 91-96 illustrate the relationships between aluminum concentrations in the sediments from this study and the concentrations of arsenic, cadmium, copper, chromium, lead, and zinc in the samples. The lower and upper 95%

confidence intervals for reference areas from Schropp et al. (1990) are included on the figures for each metal. Also shown are the Spearman-rank correlation coefficients for the data from this study. The concentrations of all trace metals measured except silver were highly correlated ($p<0.0001$) with the concentrations of aluminum; the coefficients ranged from 0.449 for cadmium to 0.962 for iron. Along with iron the concentrations of nickel, chromium, tin, and zinc were very highly correlated with aluminum (all correlation coefficients > 0.9).

The concentrations of arsenic, although highly correlated with aluminum, were within the 95% confidence intervals expected for reference sediments (Figure 91). In contrast, the concentrations of cadmium, copper, chromium, lead, and zinc in some samples exceeded the expected concentrations. In approximately 30 samples the concentrations of cadmium exceeded the concentrations expected from the aluminum content (Figure 92). Similarly, many samples with relatively high aluminum concentrations had excess levels of chromium and copper (Figures 93, 94). Among these six trace metals the concentrations of lead and zinc were most elevated most frequently (Figures 95, 96).

These data suggest that, based upon the metal-to-aluminum ratios, some samples from the study area had excess trace metals concentrations, ostensibly due to anthropogenic sources. As exemplified with data from the lower Miami River, Schropp et al. (1990) interpret excess metals concentrations as accumulations of these elements from anthropogenic sources on fine-grained particles. These observations, if they correctly portray metals-aluminum ratios (see cautionary note above), would suggest that some portions of the trace metals concentrations in the South Carolina/Georgia estuaries were contributed by human sources.

Comparisons of toxicant concentrations with sediment guidelines. The concentrations of all 27 substances for which numerical guidelines (Long et al., 1995b) exist were compared to the guideline values to identify which toxicants may have been elevated (Table 13). Although silver showed a strong correlation with urchin fertilization in Charleston Harbor (Table 9) and St. Simons Sound (Table 11), none of the silver concentrations exceeded the ERL concentration of 1.0 ppm. Arsenic exceeded the ERL value of 8.2 ppm in 64 samples but not the ERM value of 70 ppm. The concentrations of cadmium, chromium, copper, lead, and zinc exceeded their respective ERL values in 3-9 samples. The concentrations of mercury and nickel were elevated in 12 and 33 samples, respectively, relative to the ERL values, but Long et al. (1995b) reported relatively low confidence in these values. The mercury concentration in one sample from the lower Cooper River (station H1-4) exceeded the ERM value of 0.71 ppm.

The concentrations of all individual PAHs were elevated relative to respective ERL values in 4 to 44 samples (Table 13). In addition, the concentrations of anthracene, pyrene, and the sum of low molecular weight PAHs exceeded their respective ERM values in one or two samples (station D2-1 in the lower Ashley River, station B2-1 in the Brunswick Harbor, and station F2-1 in Terry Creek). Chlorinated hydrocarbon (PCBs, DDTs) were elevated in numerous samples relative to ERL values, but did not exceed the ERM values in any samples.

Based upon these data, it appears that many samples were not highly contaminated and a few were moderately contaminated, and none were highly contaminated. Samples in which all chemical concentrations were lower than the respective ERL values rarely would be expected to cause toxicity (i.e., <13% of samples in amphipod survival tests, Long et al., in prep.). Samples in which toxicant concentrations exceeded 1 to 10 ERL values, but were lower than all the ERM values, may be toxic in some cases, but not frequently (10-30% of samples in amphipod survival tests; Long et al., in prep.). Samples in which only one or two chemicals exceeded the ERM values would be expected to cause toxicity in only 30-40% of samples in amphipod survival tests (Long et al., in prep).

Therefore, although some trace metals were elevated in concentrations relative to both the aluminum content of the sediments and the ERL values, only one of these concentrations was above an ERM value. Also, only one or two samples had very high concentrations of PAHs and none had high concentrations of chlorinated substances. None of the chemical concentrations exceeded any of the five proposed national sediment quality criteria (U. S. EPA, 1994). As a consequence, a high degree of toxicity would not be expected in these samples, and, indeed, only a few showed toxicity in the amphipod survival tests. However, the chemical concentrations exceeded numerous ERL values and could be expected to cause toxicity in highly sensitive bioassays, such as the urchin fertilization and Microtox tests, and, indeed, these tests frequently showed toxicity in many samples.

Relationships between toxicity and concentrations of selected toxicants. The relationships between measures of toxicity and the concentrations of some substances were examined further with scatterplots when the correlations were significant and respective guideline values were exceeded. The scatterplots were prepared to provide visual evidence that some substances ostensibly indicated as correlated with toxicity actually showed a reasonable pattern of association and were elevated in concentration in the most toxic samples. Most of the scatterplots were prepared for the Microtox and sea urchin test results, since only two samples showed high toxicity (one in the Savannah River and one in St. Simons Sound) in the amphipod tests, and, consequently, most chemicals showed weak correlations with amphipod survival.

The concentrations of total ammonia and un-ionized ammonia were determined for the water overlying the sediments in the amphipod exposure chambers. The two samples in which amphipod survival was lowest (0.0% and 4.0% survival) had relatively low concentrations of un-ionized ammonia - the most toxic form of ammonia (Figure 97). The Spearman-rank correlation was significant, but indicated a positive association, whereas a negative association would be expected if ammonia were a major contributor to toxicity. Five of the samples tested had un-ionized ammonia concentrations that exceeded the No Observable Effects Concentration for *Ampelisca abdita* (approximately 0. 236 mg/L (from Kohn et al., 1994); none exceeded the LC50 concentration 0.83 mg/L.

In the sea urchin fertilization tests, ammonia concentrations were measured in the porewaters used in the toxicity tests. The Spearman-rank correlation between fertilization success and un-ionized ammonia was highly significant and the scatterplot shows a relatively consistent pattern of decreasing fertilization success with increasing ammonia concentrations (Figure 98). However, many samples with very low levels of ammonia were highly toxic, and only one sample exceeded the Lowest Observed Effects Concentration (LOEC) of 800 ug/L for this bioassay test; indicating other factors must have caused or contributed to toxicity. Therefore, it appears that no more than one of the 147 samples had concentrations of un-ionized ammonia sufficiently high to contribute substantially to toxicity in this test.

In sharp contrast, the sea urchin development bioassay is known to be highly sensitive to the presence of ammonia in the porewater; the LOEC concentration is 90 ug/L. Results of the embryo development tests were highly variable among samples with un-ionized ammonia concentrations less than the LOEC. However, as ammonia concentrations increased above the LOEC, percent normal development diminished rapidly. Many of the samples had un-ionized ammonia concentrations greater than 90 ug/L and all of those samples were highly toxic to embryo development (Figure 99).

To account for the possible additive effects of numerous chemicals occuring in mixtures, mean ERM quotients were calculated as the average of 25 chemical concentrations divided by their respective ERM values. As indicated in Table 9, the correlations between the results of the Microtox and two sea urchin tests and the mean ERM quotients were significant for the combined study area data set (n = 147). In the Microtox tests a relatively consistent pattern of decreasing light production with increasing mean ERM quotients was apparent (Figure 100). Several of the samples with highest mean ERM quotients (>0.2) were highly toxic; however, many more samples with considerably lower concentrations of these mixtures also were highly toxic and the two samples with the highest concentrations were not toxic. In addition, the correlations between microbial bioluminescence and mean ERM

quotients were relatively weak, although significant, in the Charleston Harbor and St. Simons Sound samples and non-significant in the Savannah River samples (Tables 9, 10 and 11). Therefore, this relationship between microbial bioluminescence and the concentrations of complex chemical mixtures showed relatively high variability and inconsistency.

Similarly, the relationship between the mean ERM quotients and sea urchin fertilization was relatively inconsistent (Figure 101), despite the observations of significant correlations in samples from the Savannah River and St. Simons Sound (Tables 10 and 11). Although, a large number of samples with high fertilization success and low chemical concentrations clustered together, there was no strong and consistent pattern of decreasing fertilization with increasing chemical concentrations. The two samples with highest chemical concentrations were among the least toxic in this test.

The strongest associations between the mean ERM quotients and toxicity were observed in the sea urchin embryo development tests (Figure 102) and the cytochrome P-450 RGS assays (Figure **103**). There was a large cluster of samples with low chemical concentrations and high percent normal embryo development and another large cluster of samples with somewhat higher chemical concentrations and very low percent normal development. The correlations were significant for the samples from the Savannah River and all samples combined, but not for the St. Simons Sound samples, where one outlier (station P1) with the highest concentrations was not toxic. Results of the cytochrome P-450 RGS assays showed a strong pattern of increasing induction with increasing concentrations of total PAHs (Figure 104). This is a pattern that was expected and observed in previous studies (Fairey et al., 1996), especially because high molecular weight PAHs are strong inducers of the assay response.

The correlation between the concentrations of copper and results of the Microtox bioassays were highly significant in the Charleston Harbor area (Table 6). The scatterplot indicated a consistent pattern of decreasing light production with increasing copper concentrations (Figure 105). All five samples with copper concentrations greater than the ERL value were highly toxic and the sample with the highest single concentration (>75 ppm, station CHP 10 in Charleston Harbor) was among the most toxic. Microtox results were highly variable and scattered among samples with copper concentrations less than the ERL value.

Another group of chemicals that showed a strong correlation with toxicity in Charleston Harbor was the pesticides (Table 9) which were significantly correlated with urchin fertilization. However, the scatterplot (Figure 106) shows that this relationship was very inconsistent and variable and two samples (those from stations B1-3 in Winyah Bay and H4-3 in the lower Cooper River) with highest concentrations were not toxic in the urchin

fertilization tests. No guideline values are available for mixtures of total pesticides.

In the samples from the Savannah River, mixtures of trace metals, PAHs, and PCBs showed significant correlations with toxicity (Table 10). The sums of the 8 metals-to-ERMs quotients were highly correlated with urchin embryo development and many samples that had relatively high metals concentrations were highly toxic (usually 0.0% normal development (Figure 107). However, there were about 11 samples with relatively high metals concentrations that were not toxic. The concentrations of the five SEM also were highly correlated (Table 10), but when normalized to the concentrations of AVS, the correlations disappeared.

In contrast, the relationship between urchin embryo development and the concentrations of total HPAH showed a very strong correlation (Table 10) and a strong associative pattern (Figure 108). All samples with concentrations greater than the ERL value were highly toxic and many samples with low concentrations had greater than 90% normal development. There were numerous samples that were highly toxic as well that had low HPAH concentrations, but toxicity in those samples could have been associated with the presence of other substances, notably un-unionzed ammonia.

Finally for the Savannah River samples, the relationship between the concentrations of total PCBs and urchin embryo development is illustrated in Figure 109. Although the correlation was highly significant and there was a reasonable strong pattern of decreasing normal development with increasing PCB concentrations, unlike the concentrations of total HPAH, the concentrations of total PCBs exceeded the ERL value in only two samples (one of which was non-toxic). Therefore, on balance this association was not nearly as strong as observed with the total HPAHs.

In the 20 samples from the St. Simons Sound, the sample from Purvis Creek had relatively high concentrations of PCBs and mercury and low PAH concentrations and the samples from Terry Creek had the opposite: low PCB and mercury concentrations and relatively high PAH concentrations. The upper Terry Creek sample was extremely toxic and the Purvis Creek sample was not toxic. The other St. Simons Sound samples had much lower chemical concentrations. The Microtox and two sea urchin tests showed significant correlations with many different substances (Table 11), including mixtures of substances normalized to their respective ERM values.

Many of the different trace metals showed strong correlations with measures of toxicity in St. Simons Sound, including the sum of the five SEM (Figure 110) and the cumulative metals/ERM quotients (Figure 111). Both the five SEM extracted with the acid-volatile sulfides (AVS) and the eight total metals normalized to dry weight ERMs showed a strong pattern of increasing toxicity

with increasing concentrations. The sample from station F1-1 in Terry Creek had the highest concentrations of five SEM and it was highly toxic in the Microtox test. However, when the concentrations of five SEM were divided by the AVS concentrations, the correlation (Table 11) changed considerably (from rho = -0.836 to rho = +0.774), indicating no significant correspondence with toxicity in the Microtox tests. Based upon equilibrium-partitioning theory, these data suggest that although trace metals concentrations may have been elevated in some samples and they co-varied with measures of toxicity, trace metals extracted from AVS explained little of the toxicity.

Another association observed among the samples from St. Simons Sound was the correlation between measures of toxicity and the concentrations of PAHs (Table 11). In both urchin tests and in the Microtox test, there were significant correlations with the concentrations of most individual PAHs, total LPAHs, total HPAHs, and total PAHs. However, as illustrated in Figure 112, this correspondence was inconsistent and variable. Many samples with low concentrations of total PAHs were non-toxic in the urchin fertilization tests, but, only one of the samples with total PAH concentrations greater than the ERL value was toxic and two others were non-toxic in this test. In contrast, although the correlation between normal urchin development and total PAHs was lower (rho = -0.497) than in the fertilization test (rho = -0.697), the correspondence was more as expected (Figure 113). Fertilization test results were variable among samples with low total PAH concentrations, many of which were non-toxic, and as total PAH concentrations increased above the ERL value, all samples were highly toxic. None of these samples exceeded the ERM value of 44,792 ppb total PAH.

In summary, there was considerable evidence suggesting that toxicity observed in these samples was associated with elevated concentrations of mixtures of many different substances, most notably some trace metals, most PAHs, and un-ionized ammonia. Measures of toxicity often were highly correlated with indices of chemical mixtures (ERM quotients) and numerous substances co-varied with each other and with concentrations of fine-grained particles. Also, it appears that the composition of the chemical mixtures varied among the estuaries. The concentrations of some trace metals (notably, copper) exceeded background levels, exceeded effects-based guideline values, and showed strong associations with some measures of toxicity. The concentrations of some individual and classes of PAHs, similarly were elevated above effects-based guidelines, correlated with toxicity, and showed strong associative patterns with toxicity. Ammonia probably contributed to toxicity in some of samples tested for sea urchin development, but, played only a minor or no role in contributing to toxicity in the other bioassays. However, although the concentrations of some substances were elevated above background levels and effects-based guideline values and many substances showed significant correlations with toxicity; there were none that could be considered unequivocably as chemical(s) of highest concern.

Discussion and Conclusions

Generally, the concentrations of most of the potentially toxic substances differed very little among the different regions of the study area. Average concentrations of most substances were similar among all the different estuaries. Generally, many different chemicals co-occurred with each other in mixtures of differing composition. The concentrations of these mixtures, as normalized to their respective ERM values, were similar and relatively low in most samples. Several samples (from stations B1-1, B2-1, F2-1 and P1), all from tributaries of St. Simons Sound, were notably more contaminated than all others; only one of which (F2-1) was highly toxic in the bioassays.

Trace metals concentrations exceeded background levels in many samples, exceeded effects-based guideline values in some samples, were strongly correlated with some measures of toxicity, and showed a reasonable associative pattern of relatively high concentrations in the most toxic samples. Many of the trace metals co-varied with each other, occurring at relatively high concentrations in many of the same samples. However, numerous samples in all regions had SEM/AVS ratios of less than 1.0, suggesting that trace metals were not highly bioavailable in most samples. Also, only one sample had a trace metal concentration (mercury) greater than an ERM value. These data agreed very well with those from the entire Carolinian province, in which concentrations of numerous substances exceeded the ERL values, but they rarely exceeded the ERM values (Hyland et al., 1996).

Average concentrations of major organic compounds were often highest in St. Simons Sound, however, one sample from Purvis Creek and one sample from Terry Creek had relatively high concentrations of total PCBs and total PAHs, respectively, and, therefore, had the effect of elevating the average concentrations for that area. Also, average concentrations of some PAHs were somewhat higher in samples from Charleston Harbor than elsewhere. Otherwise, these substances occurred in relatively similar concentrations among the different estuaries.

The spatial patterns in chemical concentrations were unique to each estuary. In Charleston Harbor the samples from the upper Ashley and Cooper rivers and Shipyard Creek had some of the highest chemical concentrations and those from the harbor entrance and lower Wando River generally had the lowest concentrations. In Winyah Bay samples collected in Georgetown harbor had the highest concentrations of trace metals and organics, but none of these concentrations were particularly high relative to effects-based guideline values. In the Savannah River the concentrations of most chemicals were highest in samples collected directly adjacent to downtown Savannah (especially in the industrial harbors), intermediate in samples

collected upstream of downtown Savannah and in the Back River, and generally decreased toward the mouth of the river. In St. Simons Sound the concentrations of PCBs and DDTs were very high in one sample from Purvis Creek, the concentrations of PAHs and some trace metals were very high in two Terry Creek samples, the concentrations of mixtures of substances were intermediate in samples from the East River/Brunswick Harbor and Back River, and the concentrations of all chemicals were lowest in samples collected near the mouth of the estuary. Except for the DDTs, the concentrations of most chemicals in Leadenwah Creek were highest near the mouth of this tidal stream.

Results of the cytochrome P-450 RGS assays (indicative of the presence of mixtures of mixed-function oxidase-inducers) performed in Charleston Harbor, showed the highest response in a sample collected in the lower Ashley River, followed by several other samples collected nearby. The lowest responses in these tests occurred in samples from the upper Cooper River.

Toxicity was most prevalent among the Winyah Bay samples, where significant toxicity occurred in a total of 21 (47%) of all the tests combined. The incidence of overall toxicity was lower in the tests performed with samples from Charleston Harbor and Savannah River (31% and 34%, respectively), and lowest in the samples from St. Simons Sound (23%) and Leadenwah Creek (7%). The tests of amphipod survival were least sensitive, indicating significant results in 8 of 163 samples (5%) tested from all areas. In the urchin fertilization tests of 100% porewater and the microbial bioluminescence tests, 39% and 36%, respectively, of the samples were toxic. The incidence of significant toxicity was highest (62%, 50 of 81 samples) in the urchin development tests of 100% porewater.

Some of the toxicity tests showed strong concordance and agreement on the most and least toxic samples, while others demonstrated little concordance among results. The test endpoints measured with the sea urchins agreed relatively well and both showed good agreement with the Microtox tests. However, none showed good concordance with the results of the amphipod tests. Therefore, spatial patterns in toxicity, based upon all of the results were difficult to tease out of the data. The amphipod tests, the least sensitive tests performed, indicated very high toxicity in one sample from Terry Creek, a tributary to St. Simons Sound, and a sample from the upper Savannah River.

There were many samples from Charleston Harbor that were toxic in one or more of the bioassays; however, none were toxic in the least sensitive bioassay performed - the amphipod survival test. Samples indicated as toxic in one or more tests were scattered throughout the study area. No single region was remarkably toxic in all tests and there was relatively little concordance among the tests. These data suggest, therefore, that toxic samples were scattered throughout the area, not concentrated in any particular area,

and, as judged by the amphipod tests, toxicity was not severe. The Microtox tests indicated many samples from the Cooper River were toxic and only two samples were toxic from the Ashley River, whereas the urchin fertilization and copepod reproduction tests indicated that most of the Ashley River samples were toxic. Several of the most seaward stations in the lower harbor were consistently non-toxic in the tests, suggesting that toxic conditions did not extend beyond the harbor entrance.

The samples from Leadenwah Creek, a system that has historically received considerable pesticide runoff from agriculture, were not highly toxic. Only one sample showed toxicity in the Microtox tests, none were toxic in the amphipod survival tests, and a very slight decrease in urchin fertilization was observed in the porewaters of two samples.

Eight of the nine samples from Winyah Bay showed toxicity in at least one of the bioassays and toxicity was most severe in the Georgetown harbor area. Toxicity generally decreased seaward down the bay. However, the most seaward station was toxic in two tests and showed the highest fold induction rate in the cytochrome P-450 assay. Therefore, the seaward extent of toxicity was not determined.

Toxicity in St. Simons Sound was most severe in the two samples collected in Terry Creek; intermediate in samples from the Brunswick harbor area and the Turtle River (where toxicity occurred in only the urchin tests); and least toxic in the samples from the lower reaches of the Turtle River and St. Simons Sound. These data indicated that, as in Charleston Harbor, toxic conditions did not extent beyond the entrance to the estuary.

In the Savannah River stations in which toxicity was observed were scattered throughout the region and each bioassay showed somewhat different patterns in toxicity. However, three tests -the Microtox tests and both urchin tests - indicated that samples from the central portion of the region adjacent to downtown Savannah were toxic. Also, there was generally less toxicity downstream of the city. Data from the amphipod survival tests, the least sensitive bioassay performed, showed a different pattern in toxicity; the only toxic stations were those from the upper reaches of the river and from Back River.

The total study area encompassed approximately 88 km^2. By weighting the results of the toxicity tests to the sizes of the sampling strata, we were able to estimate the spatial extent of toxicity. The spatial extent of toxicity differed among the estuaries and the different tests performed. As estimated by the amphipod survival, urchin fertilization, and Microtox tests the spatial extent of toxicity throughout the entire survey area was 0.3%, 21.3%, and 47.7%, respectively. In a survey conducted in numerous estuaries throughout the entire Carolinian province, including those surveyed in the present study,

Hyland et al. (1996) reported that only one of 84 samples, representing 2% of the area of the province was toxic in *Ampelisca abdita* bioassays. They estimated that 19% of the area was toxic in solid-phase Microtox tests, whereas we estimated that 47.7% of the area within the five estuaries was toxic in our Microtox tests of solvent extracts.

Relationships between measures of toxicity and the concentrations of individual toxicants and chemical mixtures were determined in several statistical analyses. Based upon the metal-to-aluminum ratios, some samples from the study area had excess trace metals concentrations, ostensibly due to anthropogenic sources. The concentrations of nickel, chromium, tin, and zinc were highly correlated with aluminum content and the concentrations of cadmium, copper, chromium, lead, and zinc exceeded background levels. These observations would suggest that some portions of the trace metals concentrations in the South Carolina/Georgia estuaries were contributed by human sources.

However, although chemical concentrations in some samples exceeded ERL values, no more than two samples exceeded an ERM value by any amount. Also, all except two samples had mean ERM quotients of 0.2 or less, indicating that the concentrations of chemical mixtures were relatively low (Long , E. R. in press). Based upon these data, it appears that many samples were not highly contaminated, some were moderately contaminated, and none were highly contaminated. Therefore, although some trace metals were elevated in concentrations relative to both the aluminum content of the sediments and the ERL values, only one of these concentrations (mercury in one sample) was above an ERM value. Also, the concentrations of different PAHs were elevated in only one or two samples and none of the concentrations of chlorinated substances were elevated. None of the chemical concentrations exceeded any of the five proposed national sediment quality criteria (U. S. EPA, 1994). As a consequence, a high degree of toxicity in the least sensitive bioassay (amphipod survival) would not be expected in these samples, and, indeed, only a few samples showed toxicity in the amphipod survival tests. However, the chemical concentrations exceeded numerous ERL values and could be expected to cause toxicity in highly sensitive bioassays, such as the urchin fertilization and Microtox tests, and, indeed, these tests showed toxicity in many samples.

Largely because the majority of the samples indicated similarly non-toxic results in the amphipod tests, correlations between chemical concentrations and amphipod survival were not significant. A similar result was observed in a survey of the Carolinian province, in which amphipod survival was either not significantly or only weakly correlated with most substances (Hyland et al., 1996).

There was considerable evidence suggesting that toxicity observed in the other tests was associated with elevated concentrations of mixtures of many different substances, most notably, some trace metals, PAHs, and un-ionized ammonia. Measures of toxicity often were highly correlated area-wide with summed indices of chemical mixtures (total PAHs, total SEM, total metals/ERM quotients, mean ERM quotients, etc.). Also, numerous substances co-varied with each other and with concentrations of fine-grained particles. The concentrations of some trace metals (notably, copper) exceeded background levels, exceeded effects-based guideline values, and showed strong associations with some measures of toxicity. The concentrations of some individual PAHs and classes of PAHs, similarly were elevated above effects-based guidelines, correlated with toxicity, and showed strong associative patterns with toxicity. Ammonia probably contributed to toxicity in some of samples tested for sea urchin development, but, played only a minor or no role in contributing to toxicity in the Microtox, urchin fertilization and amphipod tests. Also, as expected, it appeared that the composition of the chemical mixtures varied among the different estuaries. For example, in Charleston Harbor microbial bioluminescence was correlated with many trace metal concentrations and urchin fertilization was correlated only with PAHs and other organics, while in the Savannah River microbial bioluminescence was not correlated with many chemicals and urchin fertilization was strongly correlated with many substances. In conclusion, although the concentrations of some substances were elevated above background levels and effects-based guideline values and many substances showed significant correlations with toxicity; there were none that could be considered unequivocably as chemicals of highest concern.

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Table 1. Average, minimum and maximum concentrations of selected chemicals in sediments from different regions of the study area.

	Charleston Harbor n=65	St. Simons Sound n=20	Leadenwah Creek n=4 or 9*	Upper Savannah R. n=36	Lower Savannah R. n=18	Winyah Bay n=9
Silver	0.12	0.08	<0.12	0.05	0.02	0.13
(ug/g dry wt.)	0.12-0.19	<0.02-0.48	<0.12-0.12	<0.02-0.12	0.02-0.05	<0.12-0.16
Chromium	38.3	42.9	46.9	43.5	32	74.4
(ug/g dry wt.)	4.8-258.3	5.0-89.5	13.8-66.6	5.3-75.9	4.3-64.4	28.1-112.8
Lead	19	13.3	19.5	16.6	9.3	37.8
(ug/g dry wt.)	2.5-73.9	1.6-40.1	7.6-31.3	2.3-26.3	1.9-18.6	11.1-54.2
Zinc	44.9	47.9	49	66.6	35.4	121
(ug/g dry wt.)	6.7-113.3	4.4-111.8	15.4-66.3	8.2-114.4	5.3-74.5	31.1-196.3
Sum 5 SEM	0.9	0.3	0.6	1	0.2	0.9
(umol/g dry wt.)	<0.01-13.5	<0.01-2.7	0.1-1.5	<0.01-15.4	<0.01-1.15	<0.01-2.6
5SEM/AVS	2.1	1.4	2.3	6	1.6	0.6
ratio	<0.01-15.3	<0.01-22.3	0.16-6.64	<0.01-126.6	<0.01-17.9	0.04-1.7
Sum total PAHs	2054	1974.4	178.4	1321.7	479.1	629.5
(ng/g dry wt.)	19.1-9634	27-17544	33-248	77-4279	29-1185	157-1990
Sum DDTs	0.7	3.7	1.3	2.8	<2.5	1.7
(ng/g dry wt.)	<0.01-3.1	<2.5-15.9	0.5-3.0	<0.01-8.6	<2.5	0.5-5.2
Sum PCBs	8	168.6	2.3	6.6	0.6	9
(ng/g dry wt.)	<0.01-328.7	5.8-1775.9	<0.01-7.5	<0.01-29.3	<0.01-3.9	0.4-11.2

*trace metals concentrations for 4 samples and organics concentrations for 9 samples.

Table 2. Summary of toxicity test results and mean ERM quotients for sediment samples from Charleston Harbor, Winyah Bay, and Leadenwah Cre

Station	Amphipod			Microtox		Sea urchin fertilization						Tox.	Mean ERM
No.	% survival	% of control	Signif.	(mg/ml)	signif	100% pw	signif	50% pw	signif	25% pw	signif	tally	quotient
Leadenwah Creek													
A1-1	90	105.9	ns	0.02	**	96	ns	97	ns	87.8	++	4	0.012
A1-2	91	107.1	ns	4.17	ns	97.4	ns	97.8	ns	92.2	+	1	
A1-8	82	96.5	ns	1.42	ns	97.4	ns	98.4	ns	98.6	ns	0	0.014
A2-1	87	102.4	ns	1.58	ns	99.4	ns	100	ns	99.6	ns	0	0.013
A2-3	87	102.4	ns	2.69	ns	99.6	ns	99.6	ns	98.8	ns	0	0.011
A2-7	88	103.5	ns	1.39	ns	99.2	ns	99	ns	99.4	ns	0	
A3-1	86	101.2	ns	1.09	ns	97.8	ns	99.6	ns	99.8	ns	0	0.076
A3-2	87	102.4	ns	6.6	ns	99	ns	99.4	ns	99.2	ns	0	0.06
A3-3	86	101.2	ns	3.12	ns	96	ns	99.4	ns	99.2	ns	0	
Winyah Bay													
B1-1	92	104.6	ns	0.29	*	88.4	++	96.2	ns	95.8	ns	3	
B1-2	94	106.8	ns	0.00001	***	50.2	++	89	++	96.4	ns	7	
B1-3	84	95.5	ns	0.01	**	74.8	++	95.4	ns	92.8	+	5	
B2-1	91	103.4	ns	7.66	ns	86	++	95.8	ns	97	ns	2	0.042
B3-1	93	105.7	ns	7.14	ns	98.4	ns	98.4	ns	97.4	ns	0	
B4-1	94	106.8	ns	0.0001	**	2.8	++	23	++	63.6	++	8	0.147
B5-1	88	100.0	ns	0.05	**	5	++	57.3	++	56.6	++	8	0.029
B6-2	93	105.7	ns	7.03	ns	88.4	++	96.6	ns	95.2	ns	2	
B7-1	92	104.6	ns	0.49	*	89.8	++	93.4	ns	86.6	++	5	0.036
Ashley River													
C1-1	86	101.2	ns	9.8	ns	96.2	ns	97.8	ns	92.8	ns	0	0.017
C2-4	84	98.8	ns	2.92	ns	92.6	ns	95.6	ns	84.4	++	2	0.221
C3-1	86	101.2	ns	8.46	ns	35.8	++	74.4	++	56.6	++	6	0.076
C4-1	93	109.4	ns	9.43	ns	41	++	63.2	++	73.8	++	6	0.162
C5-1	87	102.4	ns	5.83	ns	31	++	75.4	++	75.2	++	6	0.102
D1-1	91	107.1	ns	0.63	ns	98.2	ns	99.4	ns	97.8	ns	0	0.231
D1-3	85	100.0	ns	2.94	ns	94.4	ns	97.6	ns	96.4	ns	0	0.025

Table 2. (continued)

Station No.	Amphipod % survival	Amphipod % of control	Amphipod Signif.	Microtox (mg/ml)	Microtox signif	Sea urchin fertilization 100% pw	signif	50% pw	signif	25% pw	signif	Tox. tally	Mean ERM quotient
D1-4	79	92.9	ns	7.45	ns	97.6	ns	99.6	ns	98.6	ns	0	
D2-1	88	103.5	ns	2.03	ns	69	++	94	+	84.4	++	5	0.034
D2-2	90	105.9	ns	0.59	ns	29.6	++	55.8	++	54	++	6	0.061
D2-3	77	90.6	ns	2.32	ns	51	++	72.6	++	47	++	6	0.049
D3-1	81	95.3	ns	0.0004	**	12	++	89.2	++	95.8	ns	6	0.097
D3-2	91	107.1	ns	0.49	ns	85.2	++	96.4	ns	96.6	ns	4	
D3-3	88	103.5	ns	2.71	ns	72.2	++	83.2	++	69	++	6	
D4-1	84	98.8	ns	6.79	ns	94.2	ns	98	ns	95.4	ns	0	
D4-2	89	104.7	ns	1.16	ns	81	++	92.6	++	87	++	6	
D4-4	87	102.4	ns	0.65	ns	23	++	58.8	++	40.8	++	6	0.03
Cooper River													
E1-1	81	95.3	ns	3.29	ns	95	ns	96.2	ns	95.2	ns	0	
E1-2	85	100.0	ns	6.71	ns	98.4	ns	99	ns	99	ns	0	0.023
E1-3	90	105.9	ns	7.49	ns	99	ns	99.6	ns	98.4	ns	0	0.053
E2-1	85	100.0	ns	0.06	**	96.4	ns	94	+	95	ns	3	0.011
E2-2	84	98.8	ns	0.81	ns	92.2	ns	94.6	+	94	ns	1	0.037
E3-1	90	105.9	ns	7.24	ns	99.8	ns	99.6	ns	99.4	ns	0	0.079
E3-3	81	95.3	ns	0.89	ns	98.4	ns	98.8	ns	97.6	ns	0	0.013
G1-1	91	103.4	ns	0.28	*	58.8	++	94	ns	93.6	+	4	0.042
G2-1	91	103.4	ns	0.78	ns	79.6	++	91.4	+	94.2	ns	3	0.107
H1-1	92	104.6	ns	0.04	**	19.4	++	80.4	++	83.8	++	8	0.075
H1-4	87	98.9	ns	5.8	ns	78.2	++	93.2	ns	94.4	++	4	
H1-5	86	97.7	ns	0.84	ns	70	++	92.4	+	95.6	ns	3	0.047
H2-2	86	97.7	ns	7.55	ns	91.8	ns	96.6	ns	95.2	ns	0	
H2-3	88	100.0	ns	0.62	*	98	ns	98.4	ns	98.8	ns	1	0.026
H2-6	86	97.7	ns	0.17	*	98.2	ns	98	ns	96	ns	1	0.049
H3-1	91	103.4	ns	7.12	ns	97.4	ns	98.2	ns	98.8	ns	0	
H3-3	89	101.1	ns	0.47	*	94.4	ns	97.8	ns	97.6	ns	1	0.03

Table 2. (continued)

Station No.	Amphipod % survival	Amphipod % of control	Amphipod Signif.	Microtox (mg/ml)	Microtox signif	Sea urchin fertilization 100% pw	signif	50% pw	signif	25% pw	signif	Tox. tally	Mean ERM quotient
H3-5	93	105.7	ns	0.89	ns	82.8	++	97.2	ns	98	ns	2	0.108
H4-2	91	103.4	ns	3.03	ns	96.8	ns	97.2	ns	95.8	ns	0	0.119
H4-3	91	103.4	ns	7.22	ns	94	ns	95	ns	94.8	ns	0	
H4-5	94	106.8	ns	4.14	ns	91	+	96.2	ns	96.6	ns	1	0.01
H5-2	93	105.7	ns	3.84	ns	92.8	ns	97	ns	92.6	++	2	0.013
H5-4	90	102.3	ns	0.24	*	90.2	+	95.2	ns	94.4	ns	2	0.119
H5-8	96	109.1	ns	1.58	ns	96.6	ns	95.8	ns	97.6	ns	0	0.148
H6-1	92	104.6	ns	0.45	*	87.6	++	96.8	ns	93.8	+	2	0.177
H6-2	88	100.0	ns	0.32	*	84.8	++	96.4	ns	98	ns	3	0.065
H6-3	93	105.7	ns	7.29	ns	96.2	ns	97.6	ns	96.4	ns	0	
H7-1	88	100.0	ns	0.22	**	97	ns	99	ns	98.6	ns	2	0.108
H8-1	93	105.7	ns	0.33	*	85.2	++	97.4	ns	98.4	ns	3	0.088
Wando River													
F1-1	93	105.7	ns	5.29	ns	82.2	++	93.4	ns	86.8	++	4	0.133
F1-2	97.5	110.8	ns	0.19	*	88.4	++	96.4	ns	95	ns	3	0.102
F1-3	93	105.7	ns	7.3	ns	94.4	ns	95.6	ns	94.8	ns	0	0.078
F2-1	87	98.9	ns	4.38	ns	90.6	+	92	ns	84.6	++	3	0.062
F2-2	90	102.3	ns	7.53	ns	87.2	++	95	ns	93.2	++	4	0.064
F2-4	91	103.4	ns	3.63	ns	94	ns	97.4	ns	94.8	ns	0	0.027
North Inlet													
NIOL	84	95.5	ns	3.02	ns	97.6	ns	97.2	ns	93.2	+	1	0.101
NIOL	90	105.9	ns	1.46	ns	99.8	ns	99.8	ns	99.2	ns	0	0.128
NIOL	85					97.6	ns	98.2	ns	98.8	ns	0	
NIOL	88											na	
NIOL	89					97.4	ns	99.2	ns	98.8	ns	0	
NIOL	88											na	

Table 2. (continued)

Station	Amphipod			Microtox		Sea urchin fertilization						Tox.	Mean ERM
No.	% survival	% of control	Signif.	(mg/ml)	signif	100% pw	signif	50% pw	signif	25% pw	signif	tally	quotient
Charleston Harbor Project													
CHP1	91	103.4	ns	3.76	ns	68.8	++	91.2	++	94.6	ns	4	0.172
CHP2	90	105.9	ns	7.48	ns	99.8	ns	98.6	ns	99.4	ns	0	0.117
CHP3	84	98.8	ns	0.02	**	91.2	ns	98.6	ns	97.6	ns	2	0.026
CHP4	83	97.7	ns	1.16	ns	66.6	++	71.4	++	68.8	++	6	0.043
CHP5	85	100.0	ns	3.88	ns	87.6	++	92.4	++	91	++	6	
CHP6	82	96.5	ns	4.92	ns	42.4	++	66.4	++	56.8	++	6	0.018
CHP7	85	100.0	ns	0.03	**	5	++	70.6	++	89.8	++	8	
CHP8	87	102.4	ns	2.58	ns	92.2	ns	93	++	90.8	++	4	0.096
CHP9	91	103.4	ns	1.01	ns	91.4	+	95.4	ns	97.2	ns	1	0.016
CHP10	95	108.0	ns	0.002	**	89.2	++	95.2	ns	93.4	+	5	0.067
CHP11	88	100.0	ns	3.45	ns	87.6	++	91.6	++	84.3	++	6	0.08

ns non-significant

^ NMFS 93-146 to 93-186 compared to reference 177. NMFS 93-196 to 93-237 compared to reference 227.

\+ statistically significant for Dunnett's t-test at 0.05

++ statistically significant for Dunnett's t-test at 0.01

* statistically significant for Mann-Whitney

** statistically significant for Mann-Whitney and Dunnetts

*** statistically significant for Mann-Whitney, Dunnetts, and Distribution-free

Table 3. Summary results of cytochrome P-450 RGS assays and melobenthic copepod reproduction bioassays on selected samples from Charleston Harbor and vic

STATION No.	P-450 RGS P-450 Assay CAS Lab.Id.	P-450 RGS Average fold nduction (10ul	P-450 RGS B (a) P Equiv. (ug/g)	copepodite production	Signif	naupliar production	Signif	total production	Signif	clutch size	Signif
Leadenwah Creek											
A1-8				61.67		327.00		388.67		14.00	*
Winyah Bay											
B1-1	21	12.14	18.8								
B1-2	22	18.43	25.57								
B1-3	23	24.71	37.39								
B2-1	24	9.81	11.97								
B3-1	25	4.19	4.22	2.00		5.33		95.33		100.67	13.24
B4-1	26	5.10	4.59								
B5-1	27	4.29	1.76								
B6-2	28	4.76	4.57								
B7-1	29	26.62	37.4								
Charleston Harbor											
CHP3				59.67		434.33		494.00		13.96	*
CHP4				1.75	*	162.00	*	163.75		8.79	*
CHP6				13.00		129.67		142.67		12.06	*
D1-1	19	37.71	18.68								
D1-3	20	48.67	24.44								
D1-4				11.33		223.00		234.33		10.48	*
D2-2	18	118.38	48.55	23.00		235.00		258.00		13.56	*
D3-1	14	67.70	42.19								
D3-2	16	50.00	55.14								
D3-3	15	67.90	86.33								
D4-1	17	56.52	80.48								
D4-2	13	38.80	17.93								
D4-4	12	36.40	12.42								

Table 3 continued

STATION No.	P-450 RGS P-450 Assay CAS Lab.Id.	P-450 RGS Average fold nduction (10ul	P-450 RGS B (a) P Equiv. (ug/g)	copepodite production	Signif	naupliar production	Signif	total production	Signif	clutch size	Signif
E2-2				1.00		116.67		117.67		9.93	*
E3-1				0.00		101.00		101.00		11.90	*
G1-1	2	32.90	36.21								
G2-1	3	59.70	70.39	18.00		183.67		201.67		13.84	
H1-1	1	15.67	7.31								
H1-4	4	14.67	5.31								
H1-5	5	37.90	47.81								
H2-2	6	10.00	3.5								
H2-3	7	26.10	18.42								
H3-1				6.67		201.33		208.00		13.42	
H4-5				10.67		123.33		134.00		13.50	
H5-4	8	7.76	3.19								
H5-8											
H6-1	9	9.19	3.38	15.33		140.00		155.33		13.41	
H6-2	10	10.38	10.32								
H8-1	11	7.43	9.09	7.00		175.00		182.00		13.17	
NIOL Ref 1	batch 1			58.00		319.67		377.67		17.80	
NIOL Ref 1	batch 2			17.25		261.75		279.00		13.55	
NIOL Ref 1	batch 3			14.67		250.67		265.33		15.39	
USC lab ctls.	batch 2			3.33		203.00		206.33		13.92	
USC lab ctls.	batch 3			44.25		329.75		385.00		12.06	

* significantly different from controls ($p<0.05$)

Table 4. Summary of toxicity test results and mean ERM quotients for sediment samples from the Savannah River.

Station	Amphipod		Microtox		Sea urchin fertilization						Sea urchin development						Tox.	Mean ERM
No.	% control	signif	(mg/ml)	signif	100% pw	signif	50% pw	signif	25% pw	signif	100% pw	signif	50% pw	signif	25% pw	signif	tally	quotient
Upper Savannah River																		
A1-1	4	@~	3.89	ns	99.6	ns	99.2	ns	98.6	ns	83.2	ns	87.8	ns	88.4	ns	2	0.048
A1-2	89	@	3.87	ns	99	ns	99.4	ns	98.8	ns	93	ns	94	ns	91.4	ns	1	0.020
A1-3	84	@	0.23	**	99	ns	98.4	ns	99.4	ns	95	ns	94.6	ns	92.4	ns	3	0.064
A2-2	87	ns	0.68	ns	99.8	ns	99.2	ns	99	ns	90.4	ns	90.4	ns	91.6	ns	0	0.065
A2-3	95	ns	0.23	**	98.4	ns	99.4	ns	98.4	ns	25.2	++	92.4	ns	94	ns	4	0.055
A2-4	90	@	3.98	ns	99.6	ns	99.2	ns	99.8	ns	88.8	ns	92.6	ns	95.6	ns	1	0.045
Downtown Savannah																		
B1-1	101	ns	3.82	ns	99	ns	99	ns	98.6	ns	93.2	ns	94.8	ns	95.2	ns	0	0.034
B1-2	100	ns	3.79	ns	99.2	ns	99	ns	98.2	ns	92	ns	91.4	ns	91.4	ns	0	0.011
B1-5	103	ns	3.84	ns	98.8	ns	99.6	ns	98.6	ns	92.8	ns	93.4	ns	93.6	ns	0	0.015
B2-1	99	ns	0.17	**	3.4	++	86.7	ns	96.8	ns	0	++	0	++	0	++	10	0.039
B2-3	99	ns	0.18	**	5.2	++	67	++	95	ns	0.8	++	0	++	49.6	++	12	0.076
B2-4	99	ns	0.57	ns	7.4	++	88	ns	98.2	ns	0	++	0	++	87.2	ns	6	0.132
B3-3	101	ns	0.12	**	1.4	++	78.6	++	98.4	ns	0.8	++	0.2	++	88	ns	10	0.039
B3-5	104	ns	0.20	**	0.8	++	53.2	++	96.6	ns	0	++	0	++	0.2	++	12	0.097
B3-6	97	ns	0.34	*	0.6	++	72.8	++	96.8	ns	0	++	0	++	16.4	++	11	0.126
B4-4	104	ns	0.15	**	98.6	ns	99.4	ns	98.4	ns	92.8	ns	95.6	ns	93.6	ns	2	0.022
B4-5	108	ns	0.15	**	63	++	94.2	ns	96.2	ns	0	++	0.6	++	95.4	ns	8	
B4-6	102	ns	0.38	*	55.4	++	95	ns	98.8	ns	0	++	0	++	93.6	ns	7	0.080
B5-1	102	ns	5.08	ns	95	ns	99.4	ns	99	ns	0	++	76.8	+	94.8	ns	3	0.065
B5-2	104	ns	6.77	ns	93	ns	98.2	ns	98.2	ns	0	++	62.4	++	91.2	ns	4	0.142
B5-3	101	ns	0.08	***	8.6	++	87.4	ns	94.8	ns	0	++	0	++	2.8	++	11	0.074
B6-1	101	ns	6.38	ns	98.4	ns	98.8	ns	99.6	ns	0	++	92.5	ns	89.8	ns	2	0.042
B6-2	96	ns	0.80	ns	97.8	ns	99.8	ns	99.2	ns	0	++	75	++	88.8	ns	4	0.068
B6-3	98	ns	0.12	**	95.8	ns	98.2	ns	98.8	ns	0	++	0	++	88.8	ns	6	0.071
B7-1	101	ns	0.07	***	71.8	++	96.6	ns	96.4	ns	0	++	0.6	++	93.6	ns	9	0.035
B7-2	96	ns	3.93	ns	95	ns	99.2	ns	98.6	ns	0	++	73	++	93	ns	4	0.072
B7-3	109	ns	5.16	ns	87	ns	98	ns	99	ns	0	++	92.6	ns	95.4	ns	2	0.090
B8-1	98	ns	3.82	ns	95.4	ns	98	ns	99.6	ns	0	++	25.4	++	93.2	ns	4	0.075
B8-2	99	ns	4.22	ns	98.4	ns	99.2	ns	98.8	ns	0.4	++	85.2	ns	93.8	ns	2	0.104

Table 4. (continued)

Station	Amphipod		Microtox		Sea urchin fertilization						Sea urchin development						Tox.	Mean ERM
No.	% control	signif	(mg/ml)	signif	100% pw	signif	50% pw	signif	25% pw	signif	100% pw	signif	50% pw	signif	25% pw	signif	tally	quotient
B8-3	97	ns	0.40	ns	10.4	++#	80.2	++#	99.4	ns#	2.2	++#	0.2	++#	56.6	++#	10	0.067
B9-1	100	ns	0.11	**	48.4	++#	96.8	ns	99.8	ns#	0	++#	0	++#	91.4	ns#	8	0.061
B9-2			0.21	**														
B9-3	100	ns	0.10	**	31.6	++#	97.4	ns#	99.0	ns#	0	++#	0	++#	94.2	ns#	8	0.057
Back River																		
C1	91	@	0.07	**	99.8	ns	99.6	ns	95.2	ns	91.4	ns	98	ns	98.6	ns	3	0.056
C2	91	ns	0.08	**	99.2	ns	99.8	ns	98.8	ns	64.4	++	97.6	ns	96.6	ns	4	0.094
C3	97	ns	5.03	ns	100.0	ns	99.6	ns	100.0	ns	98.6	ns	98	ns	96.4	ns	0	0.012
Lower Savannah River																		
D1,1-1	91	ns	0.09	**	100.0	ns	100.0	ns	99.4	ns	0	++	91.6	ns	97.6	ns	4	0.047
D1,2-2	101	ns	4.97	ns	97.2	ns	99.2	ns	99.2	ns	96.4	ns	96.4	ns	98.8	ns	0	0.038
D1,3-1	97	ns	0.09	**	71.2	++	98.6	ns	99.2	ns	3.6	++	0	++	14.6	++	10	0.051
D2,1-1	94	ns	5.04	ns	99.0	ns	99.6	ns	99.4	ns	96.2	ns	97.8	ns	98.4	ns	0	0.044
D2,2-2	96	ns	7.53	ns	98.6	ns	99.2	ns	99.4	ns	98.2	ns	98.2	ns	98.2	ns	0	0.024
D2,3-1	87	ns	0.61	*	97.6	ns	98.4	ns	96.8	ns	98.2	ns	97	ns	98.2	ns	1	0.019
D3,1-4	88	@	3.88	ns	99.6	ns	100.0	ns	99.8	ns	97.4	ns	98.4	ns	96.8	ns	1	0.013
D3,2-1	100	ns	2.25	ns	99.6	ns	99.6	ns	99.4	ns	98	ns	97.8	ns	98.8	ns	0	0.013
D3,3-2	96	ns	0.16	**	98.0	ns	99.4	ns	99.6	ns	19	++	0	++	97.2	ns	6	0.037
South Channel																		
E1,2-1	100	ns	0.56	ns	100.0	ns	100.0	ns	99.4	ns	96.8	ns	98.6	ns	98	ns	0	0.023
E1,3-1	100	ns	4.84	ns	100.0	ns	99.6	ns	99.6	ns	97.6	ns	98.2	ns	97.6	ns	0	0.044
E1-1	100	ns	0.38	ns	99.8	ns	99.8	ns	99.6	ns	64.6	++	98.4	ns	97.4	ns	2	0.029
E2-1	94	ns	5.24	ns	99.6	ns	99.4	ns	99.6	ns	97.8	ns	98.6	ns	98.2	ns	0	0.041
E2-2	102	ns	3.82	ns	99.6	ns	99.4	ns	99.4	ns	98.4	ns	98.2	ns	98	ns	0	0.041
E2-3	99	ns	0.29	ns	100.0	ns	99.2	ns	98.8	ns	36.8	++	96.8	ns	97.6	ns	2	0.048
E3-2	94	ns	0.24	*	99.6	ns	99.8	ns	99.0	ns	97.8	ns	95.8	ns	98.8	ns	1	0.032
E3-5	95	ns	0.01	**	95.0	ns	99.6	ns	99.2	ns	1	++	0	++	79.2	++	8	0.051
E3-9	96	ns	0.12	**	99.8	ns	99.4	ns	100.0	ns	3	++	0	++	97.2	ns	6	0.053

Table 4. (continued)

Station No.	Amphipod % control	signif	Microtox (mg/ml)	signif	Sea urchin fertilization 100% pw	signif	50% pw	signif	25% pw	signif	Sea urchin development 100% pw	signif	50% pw	signif	25% pw	signif	Tox. tally	Mean ERM quotient
Savannah harbors																		
F1	101	ns	0.47	ns	7.2	++#	95.2	ns#	99.4	ns#	2.6	++#	0	++#	29	++#	8	0.093
F2	101	ns	0.32	**	10.4	++#	93.2	ns#	97.0	ns#	2	++#	0.2	++#	0.8	++#	10	0.088
G1	97	ns	0.16	**	72.8	++	97.2	++	98.8	ns	0	++	0	++	78.4	+	11	0.114
G2	102	ns	0.59	ns	86.8	ns	94.4	ns	98.2	ns	0.2	++	0	++	28.8	++	6	0.091
H1	103	ns	0.25	**	11	++	94.6	ns	98.2	ns	0	++	0	++	0.6	++	10	0.137
H2	98	ns	0.21	**	88.2	ns	96.4	ns	99.4	ns	0	++	0	++	89.8	ns	6	0.111
H3			0.19	**														0.111
North Inlet																		
Ref. No. Inlet 216			0.84	ns														
Ref. No. Inlet 242			0.82	ns														
Ref. No. Inlet 273			0.77	ns							91.2		93.5		93.5			
Ref. No. Inlet (Lower Savannah)					99.6	ns	100	ns	99.8	ns	31.2	++	99	ns	99.4	ns		
Ref. No. Inlet (upper Savannah)					98.4	ns	98.6	ns	99.2	ns	1.5	++	92.5	ns	90	ns		
Ref. Redfish Bay (Lower Savannah)					99.3		99.0		99.3		99.2		98.4		98.3			
Ref. Redfish Bay (upper Savannah)					98.8		99.4		99.3		91.2		93.5		93.5			

Note: MSL samples 94-266 to 94-306 collected from Upper Savannah.
MSL samples 94-217 to 94-248 samples collected from Lower Savannah.

^ Upper Savannah samples compared to reference 273. Lower Savannah samples compared to references 216 and 242.
ns non-significant
\+ statistically significant for Dunnett's t-test at 0.05
++ statistically significant for Dunnett's t-test at 0.01
* statistically significant for Mann-Whitney
** statistically significant for Mann-Whitney and Dunnetts
*** statistically significant for Mann-Whitney, Dunnetts, and Distribution-free
@ sample mean was statistically different from control
~ sample mean 80% or less than the control
# sample assayed and statistically compared to Redfish Bay (Lower Savannah)

Table 5. ımary of toxicity test results and mean ERM quotients for se ent samples from the St. Simons Sound.

Station	Amphipod		Microtox		Sea urchin fertilization						Sea urchin development						Tox.	Mean ERM
No.	% control	signif	(mg/ml)	signif	100% pw	signif	50% pw	signif	25% pw	signif	100% pw	signif	50% pw	signif	25% pw	signif	tally	quotient
upper Turtle River																		
A1 -1	95	ns	2.68	ns	98.8	ns	99.6	ns	99.6	ns	0	++	52.8	++	98.6	ns	4	0.019
A2 -2	96	ns	3.70	ns	99.0	ns	99.4	ns	99.0	ns	96.6	ns	97.80	ns	98.2	ns	0	0.033
A3 -1	95	ns	0.63	ns	100.0	ns	100.0	ns	99.4	ns	63.4	++	96.4	ns	97.4	ns	2	0.068
Brunswick Harbor																		
B1 -1	98	ns	0.27	ns	14.8	++	65.4	++	99.0	ns	2.6	++	0	++	61.6	++	10	0.228
B2 -1	100	ns	0.58	ns	93.4	ns	99.2	ns	99.6	ns	0	++	85.4	ns	98.4	ns	2	0.307
East River																		
C1 -1	101	ns	0.25	ns	23.0	++	93.2	ns	99.2	ns	3.25	++	0.004	++	7.4	++	8	0.141
C2 -1	105	ns	0.17	**	82.6	++	98.6	ns	99.6	ns	0	++	0	++	5.75	++	10	0.098
C3-1	101	ns	3.27	ns	75.4	++	98.2	ns	99.6	ns	1	++	0	++	56.6	++	8	0.090
mid-Turtle River																		
D1 -1	98	ns	3.45	ns	99.4	ns	99.2	ns	99.6	ns	58	++	96.6	ns	97.6	ns	2	0.027
D2 -1	98	ns	1.97	ns	99.8	ns	99.2	ns	99.4	ns	37.25	++	95.6	ns	96.4	ns	2	0.028
D3 -2	96	ns	3.80	ns	99.6	ns	99.2	ns	99.0	ns	96.4	ns	97.4	ns	98.4	ns	0	0.015
lower Turtle River																		
E1 -1	95	ns	0.46	ns	99.0	ns	100.0	ns	99.8	ns	3.8	++	98.2	ns	98.4	ns	2	0.041
E2 -2	97	ns	0.17	**	99.0	ns	99.8	ns	98.8	ns	87.8	ns	97.4	ns	98.5	ns	2	0.053
E3-1	85	ns	1.68	ns	99.8	ns	100.0	ns	99.2	ns	98.6	ns	98.2	ns	98.6	ns	0	0.037
Terry Creek																		
F1-1	86	@	0.01	**	95.2	ns	99.4	ns	99.4	ns	1.6	++	60.6	++	98.4	ns	7	0.065
F2-1	0	@~	0.12	**	96.2	ns	99.8	ns	99.2	ns	18.5	++	97.6	ns	98.4	ns	6	0.225
St. Simons Sd.																		
G1-1	103	ns	0.02	**	93.2	ns	98.4	ns	100.0	ns	5.4	++	0	++	95.8	ns	6	0.069
G2-1	99	ns	5.32	ns	99.8	ns	100.0	ns	99.6	ns	96.6	ns	97.2	ns	99	ns	0	0.014
G3-1	96	ns	1.00	ns	99.8	ns	99.6	ns	97.2	ns	98.6	ns	98.6	ns	98.4	ns	0	0.022
Purvis Creek																		
P1	98	ns	1.61	ns	99.4	ns	99.6	ns	99.8	ns	98	ns	99	ns	98.4	ns	0	0.470
North Inlet																		
Ref. No. Inlet			0.84	ns														
Ref. No. Inlet			0.82	ns														
Ref. Redfish Bay					99.3	ns	99.0	ns	99.3	ns	99.2	ns	98.4	ns	98.3	ns		
Ref. No. Inlet					99.6	ns	100.0	ns	99.8	ns	31.2	++	99	ns	99.4	ns		

Table 5. .ıtInued)

ns non-significant
\+ statistically significant for Dunnett's t-test at 0.05
++ statistically significant for Dunnett's t-test at 0.01
* statistically significant for Mann-Whitney
** statistically significant for Mann-Whitney and Dunnetts
*** statistically significant for Mann-Whitney, Dunnetts, and Distribution-free
@ sample mean was statistically different from control
~ sample mean 80% or less than the control

Table 6. Incidence (percent of total samples tested) of significantly toxic samples from each of six estuarine regions.

Region	Amphipod survival*	Microbial bioluminescence**	Urchin fertilization***			Urchin development***			All tests combined
			100% pw.	50% pw.	25% pw.	100% pw.	50% pw.	25% pw.	
Leadenwah Creek (n=9)	0.0	11.1	0.0	0.0	22.2	nd	nd	nd	6.7
Winyah Bay (n=9)	0.0	66.6	88.9	33.3	44.4	nd	nd	nd	46.7
Charleston Harbor (n=65)	0.0	25.4	50.8	33.8	40.0	nd	nd	nd	30.5
Savannah River (n-60)	10.0	49.2 [a]	31.7	8.3	0.0	63.9	47.5	21.3	33.5
St. Simons Sound (n=20)	10.0	25.0	20.0	5.0	0.0	65.0	35.0	20.0	22.5
North Inlet (n=4)	0.0	0.0	0.0	0.0	25.0	100 [b]	0.0 [b]	0.0 [b]	11.5

* one-way t-test ($p<0.05$)
** Mann-Whitney test ($p<0.05$)
*** Dunnett's one-tailed test ($p<0.05$)
nd = no data
[a] data for station B9-2 excluded
[b] for urchin development tests, n=2

Table 7. Spearman-rank correlations (rho, corrected for ties) among toxicity tests performed on sediments from Charleston Harbor, Winyah Bay, Leadenwah Creek, Savannah River, and St. Simons Sound.

Charleston Harbor/Winyah Bay/Leadenwah Creek

	Amphipod survival	Microtox	Urchin fertilization
Microtox	0.115 ns		
Urchin fertilization	0.221 ns	0.389 **	
P450 RGS (B[a]p equivalents)	-0.045 ns	0.082 ns	-0.112 ns
Copepod:			
• clutch size	0.265 ns	-0.260 ns	0.101 ns
• nauplii production	-0.389 ns	-0.377 ns	-0.224 ns
• copepodite production	-0.230 ns	-0.425 ns	-0.361 ns

Savannah River

	Amphipod survival	Microtox	Urchin fertilization
Microtox	0.158 ns		
Urchin fertilization	-0.329 *	0.312 *	
Urchin development	-0.345 *	0.280 *	0.664 ***

St. Simons Sound

	Amphipod survival	Microtox	Urchin fertilization
Microtox	0.012 ns		
Urchin fertilization	-0.447 *	0.502 *	
Urchin development	-0.315 ns	.390 ns	0.732 **

All areas combined

	Amphipod survival	Microtox	Urchin fertilization
Microtox	-0.031 ns		
Urchin fertilization	-0.308 ***	0.388 ***	
Urchin development	-0.368 **	0.335 *	0.701 ***

ns: $p>0.05$, *$p<0.05$, ** $p<0.001$, *** $p<0.0001$

Table 8. Estimates of the spatial extent of toxicity, expressed as kilometer^2 and percent of each area, based upon results of three toxicity tests*.

Survey Region	Total survey area (km^2)	Amphipod survival	Urchin fertilization	Microbial bioluminescence
Winyah Bay	7.3	0	3.1 (42.2%)	5.1 (70.0%)
Charleston Harbor	41.1	0	12.5 (30.4%)	17.6 (42.9%)
Leadenwah Creek	1.7	0	0	0.3 (20.1%)
Savannah River	13.1	0.2 (1.2%)	2.4 (18.4%)	7.5 (57.1%)
St. Simons Sound	24.6	0.1 (0.4%)	0.7 (2.6%)	11.4 (46.4 %)
Total area	87.8	0.3 (0.3%)	18.7 (21.3%)	41.9 (47.7%)

* Based upon bioassay responses <80% of controls

Table 9. Spearman rank correlations (Rho, corrected for ties) between measures of toxicity and chemical concentrations in sediments from Charleston Harbor, Winyah Bay, and Leadenwah Creek (n=66).

Chemical	Amphipod survival		Microbial bioluminescence		Urchin fertilization		P-450 RGS bioassay	
P450 RGS	-.165	ns	.146	ns	-.137	ns		
UAN (amphipod-start)	-.096	ns	na		na			
UAN (amphipod-end)	-.094	ns	na		na			
UAN (urchin)	na		na		-.151	ns		
silver	.040	ns	-.124	ns	-.350	*		
aluminum	.228	ns	-.375	*	-.032	ns		
arsenic	.217	ns	-.301	*	-.091	ns		
cadmium	.055	ns	-.237	ns	-.169	ns		
chromium	.217	ns	-.343	*	-.096	ns		
copper	.219	ns	-.421	**	-.173	ns		
iron	.290	ns	-.354	*	.043	ns		
mercury	.173	ns	-.195	ns	-.105	ns		
manganese	.273	ns	-.267	*	-.049	ns		
nickel	.215	ns	-.355	*	-.076	ns		
lead	.186	ns	-.318	*	-.122	ns		
selenium	.216	ns	-.299	*	-.238	ns		
tin	.269	ns	-.277	*	-.098	ns		
zinc	.218	ns	-.373	*	-.163	ns		
percent fines	.253	ns	-.412	**	-.048	ns		
percent toc	.240	ns	-.418	**	-.057	ns		
total 5 SEM	.069	ns	-.298	*	-.035	ns		
SEM:AVS ratio	.120	ns	.679	***	.238	ns		
total gc PAHs	.015	ns	-.276	*	-.272	*	.801	***
sum 8 LPAHs	.001	ns	-.320	*	-.255	*	.656	**
sum 16 HPAHs	.022	ns	-.262	*	-.274	*	.791	***
total PCBs	.071	ns	-.345	*	-.273	*	.774	***
total pesticides	.076	ns	-.308	*	-.280	*	.653	**
total DDTs	.083	ns	-.239	*	-.069	ns	.488	*
sum 9 metals/ERMs	.160	ns	-.356	*	-.084	ns	.230	ns
sum 3 cohs/ERMs	.024	ns	-.315	*	-.228	ns	.706	**
sum 13 pahs/ERMs	.031	ns	-.269	*	-.215	ns	.789	***
mean of 25 ERM quots	.031	ns	-.269	*	-.245	ns	.693	**

ns = non-significant ($p>0.05$)

* $p<0.05$; ** $p<0.001$; *** $p<0.0001$

UAN = un-ionized ammonia

SEM = simultaneously extracted metals

AVS = acid-volatile sulfides

TOC = total organic carbon

PAHs = polynuclear aromatic hydrocarbons

PCBs = polychlorinated biphenyls

ERMs = effects range median values

Table 10. Spearman rank correlations (Rho, corrected for ties) between measures of toxicity and chemical concentrations in sediments from the Savannah River (n=61).

Chemical	Amphipod survival		Microbial biolum-inescence		Urchin fertilization		Urchin development	
UAN (amphipod-start)	.433	**	na		na		na	
UAN (amphipod-end)	.320	*	na		na		na	
UAN (urchin)	na		na		-.733	***	-.688	***
silver	-.122	ns	.030	ns	-.030	ns	-.178	ns
aluminum	.055	ns	-.034	ns	-.450	**	-.550	***
arsenic	-.001	ns	-.166	ns	-.262	*	-.353	*
cadmium	.266	ns	-.417	*	-.474	**	-.538	***
chromium	.170	ns	-.108	ns	-.481	**	-.560	***
copper	.041	ns	-.061	ns	-.454	**	-.614	***
iron	.153	ns	.085	ns	-.489	**	-.627	***
mercury	-.013	ns	-.145	ns	-.483	**	-.611	***
manganese	.126	ns	.018	ns	-.549	***	-.660	***
nickel	.077	ns	-.035	ns	-.445	**	-.567	***
lead	.097	ns	-.136	ns	-.486	**	-.638	***
selenium	-.121	ns	-.108	ns	-.226	ns	-.196	ns
tin	.010	ns	-.490	ns	-.437	**	-.523	***
zinc	.153	ns	-.181	ns	-.548	***	-.669	***
percent fines	.158	ns	-.050	ns	-.435	**	-.631	***
percent toc	.146	ns	.155	ns	-.426	*	-.565	***
total 5 SEM	.199	ns	-.425	*	-.496	**	-.634	***
SEM:AVS ratio	.106	ns	-.857	***	-.328	*	.143	ns
total gc PAHs	.115	ns	.039	ns	-.383	*	-.576	***
sum 8 LPAHs	.230	ns	.000	ns	-.211	ns	-.346	*
sum 16 HPAHs	.117	ns	-.037	ns	-.462	**	-.631	***
total PCBs	.077	ns	-.075	ns	-.362	*	-.518	***
total pesticides	.163	ns	.353	*	-.144	ns	-.276	*
total DDTs	.045	ns	.221	ns	-.166	ns	-.137	ns
sum 9 metals/ERMs	.166	ns	-.179	ns	-.535	***	-.665	***
sum 3 cohs/ERMs	.084	ns	-.067	ns	-.362	*	-.514	***
sum 13 pahs/ERMs	.250	ns	-.144	ns	-.442	**	-.560	***
mean of 25 ERM quotients	.171	ns	-.161	ns	-.558	***	-.700	***

ns = non-significant (p>0.05); * p<0.05; ** p<0.001; *** p<0.0001

UAN = un-ionized ammonia. TOC = total organic carbon.

SEM/AVS = simultaneously extracted metals/acid-volatile sulfides.

PAHs = polynuclear aromatic hydrocarbons; PCBs = polychlorinated biphenyls.

cohs = chlorinated organic hydrocarbons

ERMs = effects range median values

Table 11. Spearman rank correlations (Rho, corrected for ties) between measures of toxicity and chemical concentrations in sediments from St. Simons Sound (n=20).

Chemical	Amphipod survival		Microbial biolum-inescence		Urchin fertilization		Urchin development	
UAN (amphipod-start)	0.450	ns	na		na		na	
UAN (amphipod-end)	0.206	ns	na					
UAN (urchin)					-0.546	*	-0.645	*
silver	0.424	ns	-0.256	ns	-0.664	*	-0.564	*
aluminum	0.282	ns	-0.736	**	-0.793	**	-0.484	*
arsenic	0.226	ns	-0.679	*	-0.593	*	-0.407	ns
cadmium	-0.088	ns	-0.269	ns	-0.172	ns	-0.140	ns
chromium	0.375	ns	-0.660	*	-0.868	**	-0.592	*
copper	0.165	ns	-0.692	*	-0.815	**	-0.580	*
iron	0.346	ns	-0.733	**	-0.763	**	-0.470	*
mercury	0.300	ns	-0.538	*	-0.665	*	-0.582	*
manganese	0.335	ns	-0.662	*	-0.775	**	-0.586	*
nickel	0.206	ns	-0.769	**	-0.803	**	-0.567	*
lead	0.206	ns	-0.703	*	-0.736	*	-0.440	ns
selenium	0.345	ns	-0.081	ns	-0.402	ns	-0.321	ns
tin	0.417	ns	-0.570	ns	-0.867	*	-0.560	*
zinc	0.286	ns	-0.683	*	-0.778	**	-0.464	*
percent fines	0.328	ns	-0.635	*	-0.815	**	-0.583	*
percent toc	0.152	ns	-0.703	*	-0.777	**	-0.531	*
total 5 SEM	-0.031	ns	-0.836	***	-0.486	*	-0.295	ns
SEM:AVS ratio	-0.123	ns	0.774	**	0.411	ns	0.335	ns
total gc PAHs	0.159	ns	-0.587	*	-0.697	*	-0.497	*
sum 8 LPAHs	0.097	ns	-0.685	*	-0.665	*	-0.466	*
sum 16 HPAHs	0.142	ns	-0.542	*	-0.666	*	-0.520	*
total PCBs	0.423	ns	-0.062	ns	-0.246	ns	-0.135	ns
total pesticides	0.282	ns	0.049	ns	-0.103	ns	0.098	ns
total DDTs	0.361	ns	-0.283	ns	-0.358	ns	-0.016	ns
sum 9 metals/ERMs	0.185	ns	-0.742	*	-0.777	**	-0.510	*
sum 3 cohs/ERMs	0.430	ns	-0.078	ns	-0.268	ns	-0.130	ns
sum 13 pahs/ERMs	0.194	ns	-0.601	*	-0.686	*	-0.441	*
mean 25 ERM quotients	0.286	ns	-0.608	*	-0.617	*	-0.396	ns

ns = non-significant ($p>0.05$); * $p<0.05$; ** $p<0.001$; *** $p<0.0001$

UAN = un-ionized ammonia. TOC = total organic carbon.

SEM/AVS = simultaneously extracted metals/acid-volatile sulfides.

PAHs = polynuclear aromatic hydrocarbons; PCBs = polychlorinated biphenyls.

cohs = chlorinated organic hydrocarbons

ERMs = effects range median values

Table 12. Spearman rank correlations (Rho, corrected for ties) between measures of toxicity and chemical concentrations in sediments from all South Carolina/Georgia areas (n=147).

Chemical	Amphipod survival		Microbial biolum-inescence		Urchin fertilization		Urchin development	
UAN (amphipod-start)	.510	***	na		na		na	
UAN (amphipod-end)	.487	***	na		na		na	
UAN (urchin)					-.500	***	-.676	***
sum 9 metals/ERMs	.238	*	-.356	***	-.401	***	-.632	***
sum 3 cohs/ERMs	-.303	**	-.001	ns	.055	ns	-.263	*
sum 13 pahs/ERMs	.060	ns	-.273	**	-.385	***	-.537	***
mean of 25 ERM quots	.130	ns	-.295	**	-.414	***	-.609	***

ns = non-significant ($p>0.05$); * $p<0.05$; ** $p<0.001$; *** $p<0.0001$

UAN = un-ionized ammonia. TOC = total organic carbon.

PAHs = polynuclear aromatic hydrocarbons; PCBs = polychlorinated biphenyls.

cohs = chlorinated organic hydrocarbons

ERMs = effects range median values

Table 13. Numbers of samples (out of 140 analyzed) in which ERL and ERM values (from Long et al., 1995) were exceeded.

Chemical	Number of samples exceeding ERL value	Number of samples exceeding ERM value
silver	none	none
arsenic	64	none
cadmium	8	none
chromium	9	none
copper	5	none
mercury	20	2
nickel	33	none
lead	4	none
zinc	3	none
naphthalene	4	none
2-methyl naphthalene	10	none
acenaphthylene	13	none
acenaphthene	44	none
fluorene	39	none
phenanthrene	21	none
anthracene	25	1
fluoranthene	11	none
pyrene	11	1
benzo(a)anthracene	12	none
chrysene	12	none
benz(a)pyrene	6	none
dibenzo(a,h)anthracene	6	none
sum LPAHs	8	2
sum HPAHs	31	none
total PAHs	16	none
p,p'-DDE	1	none
total DDTs	32	none
total PCBs	16	none

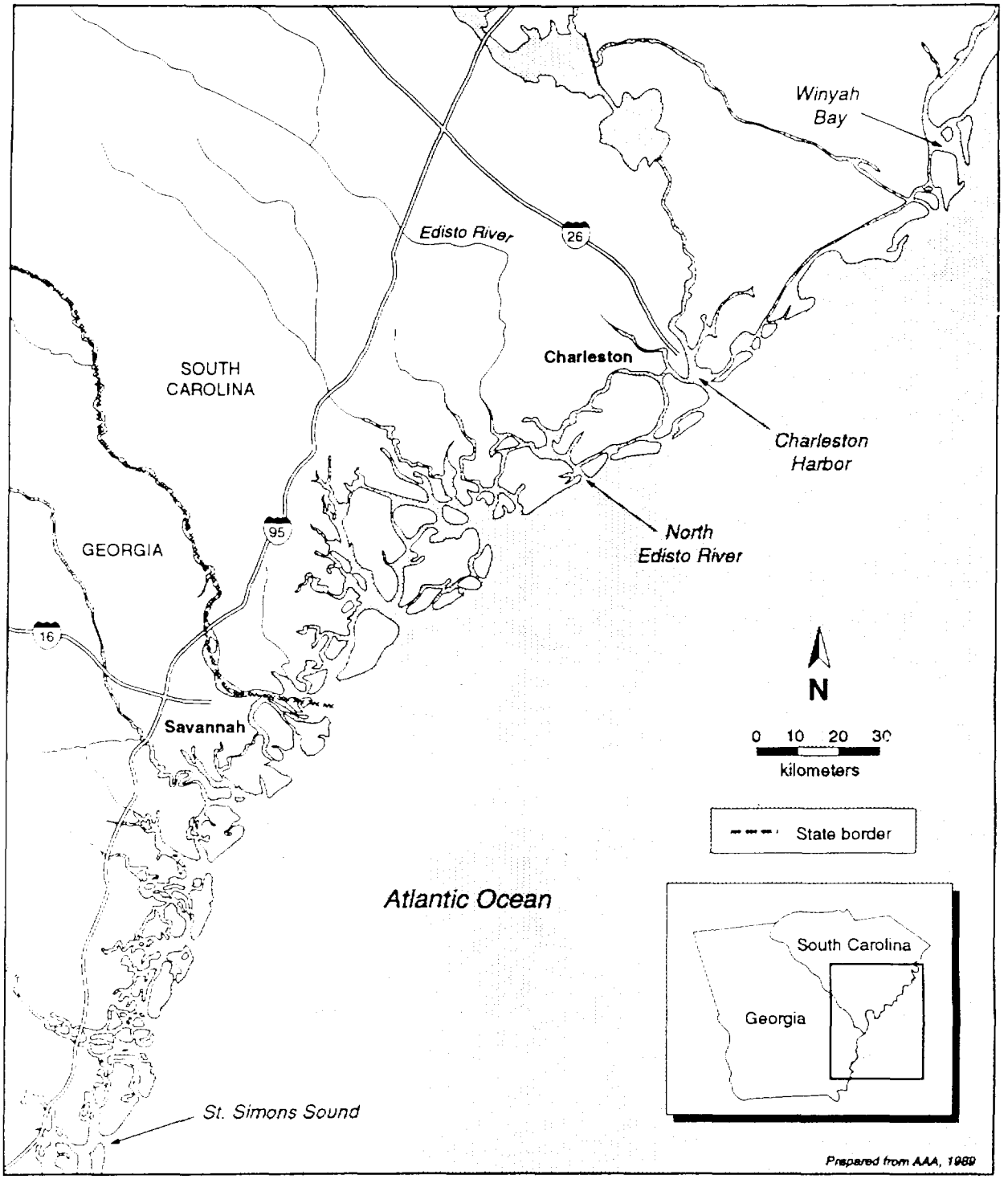


Figure 1. South Carolina and Georgia coastline

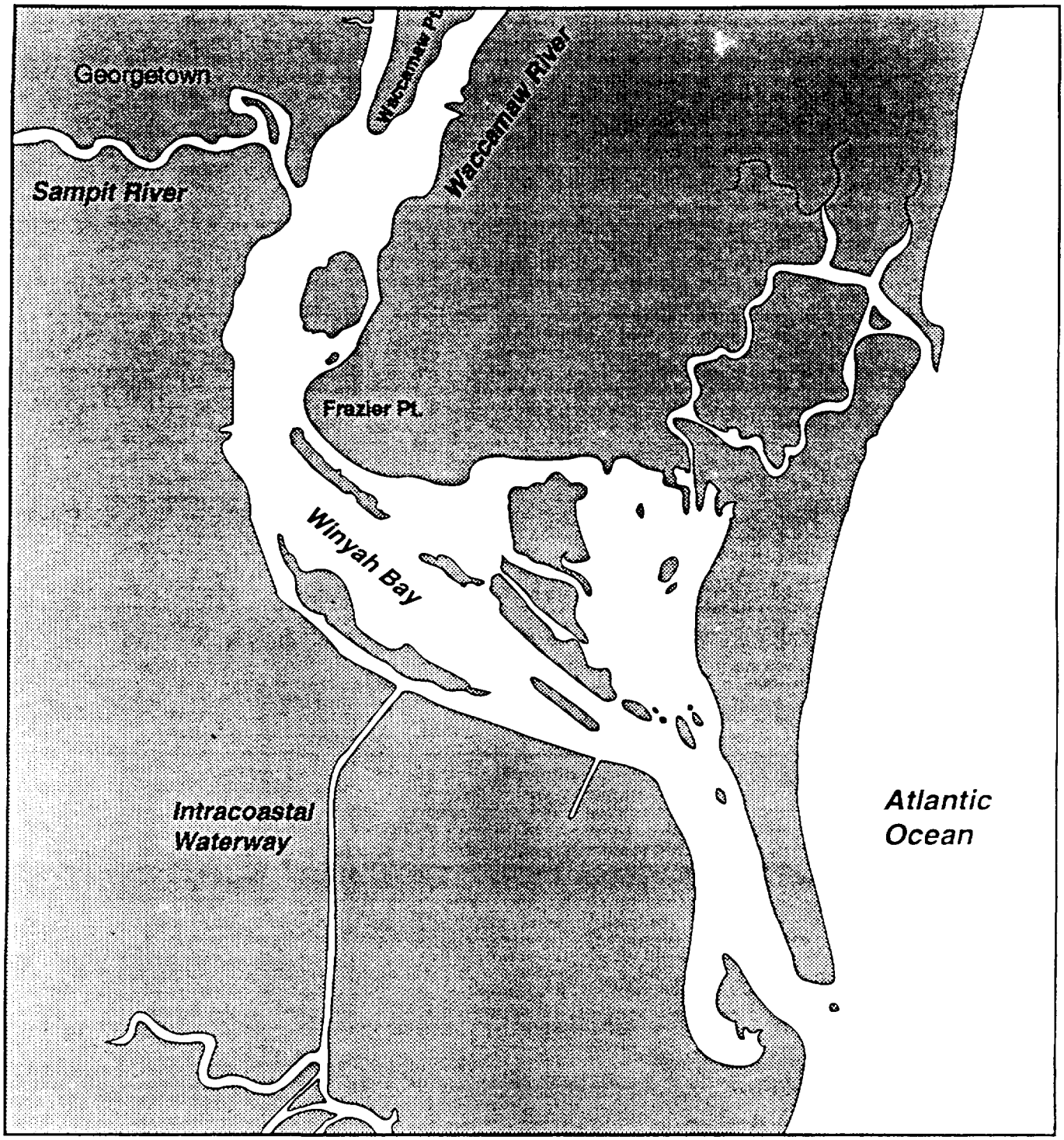


Figure 2. Winyah Bay, SC, study area.

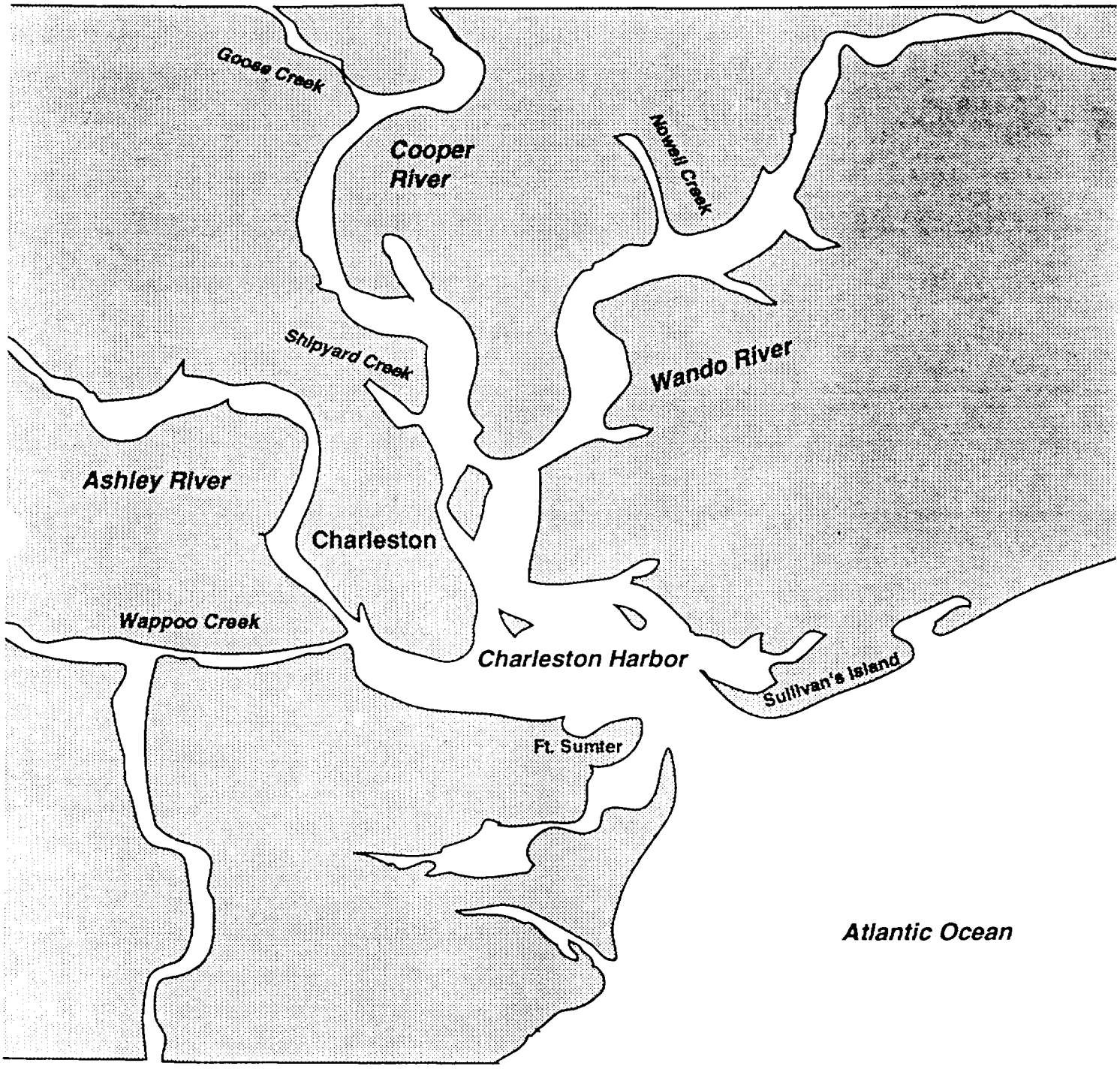


Figure 3. Charleston Harbor, SC, study area.

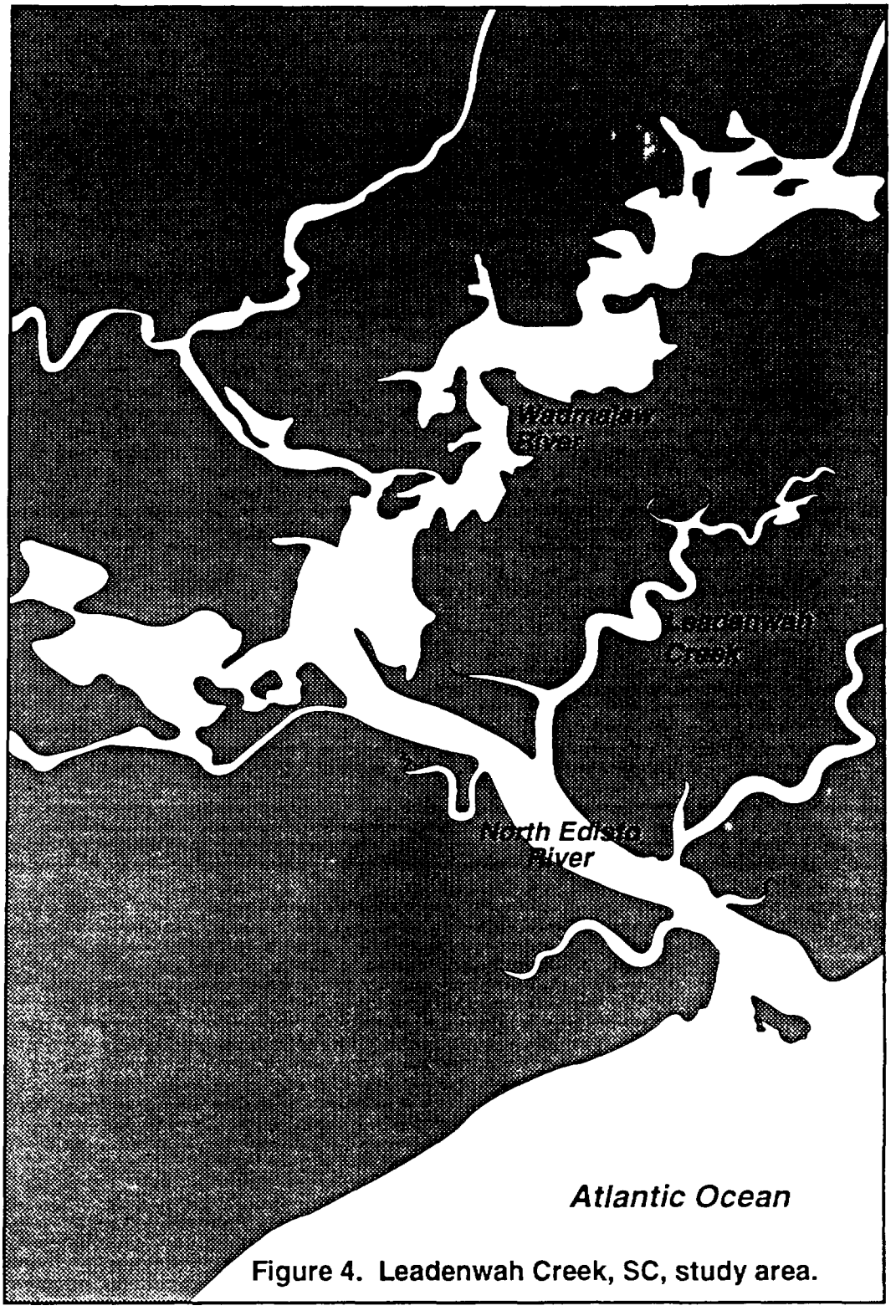


Figure 4. Leadenwah Creek, SC, study area.

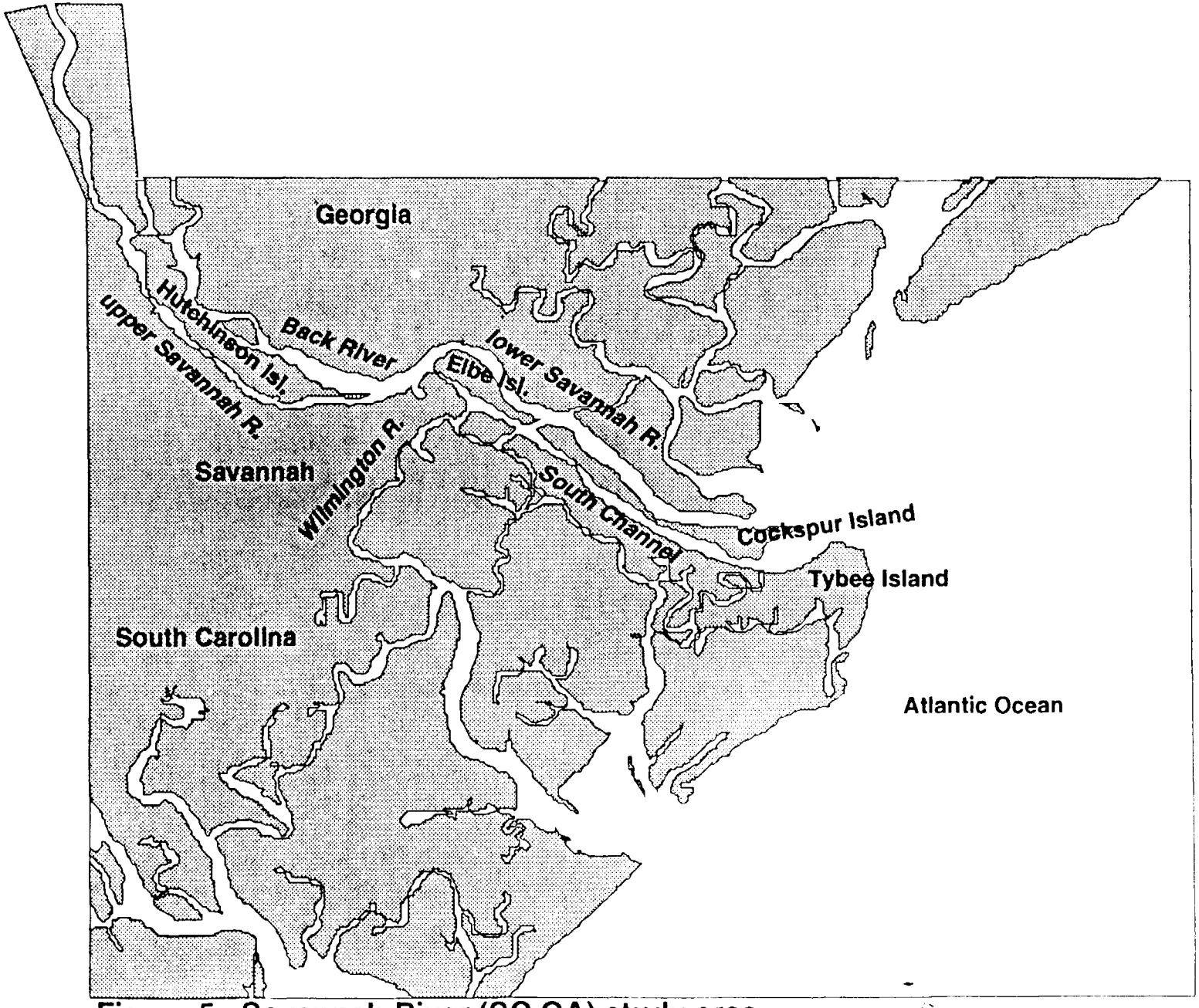


Figure 5. Savannah River (SC,GA) study area.

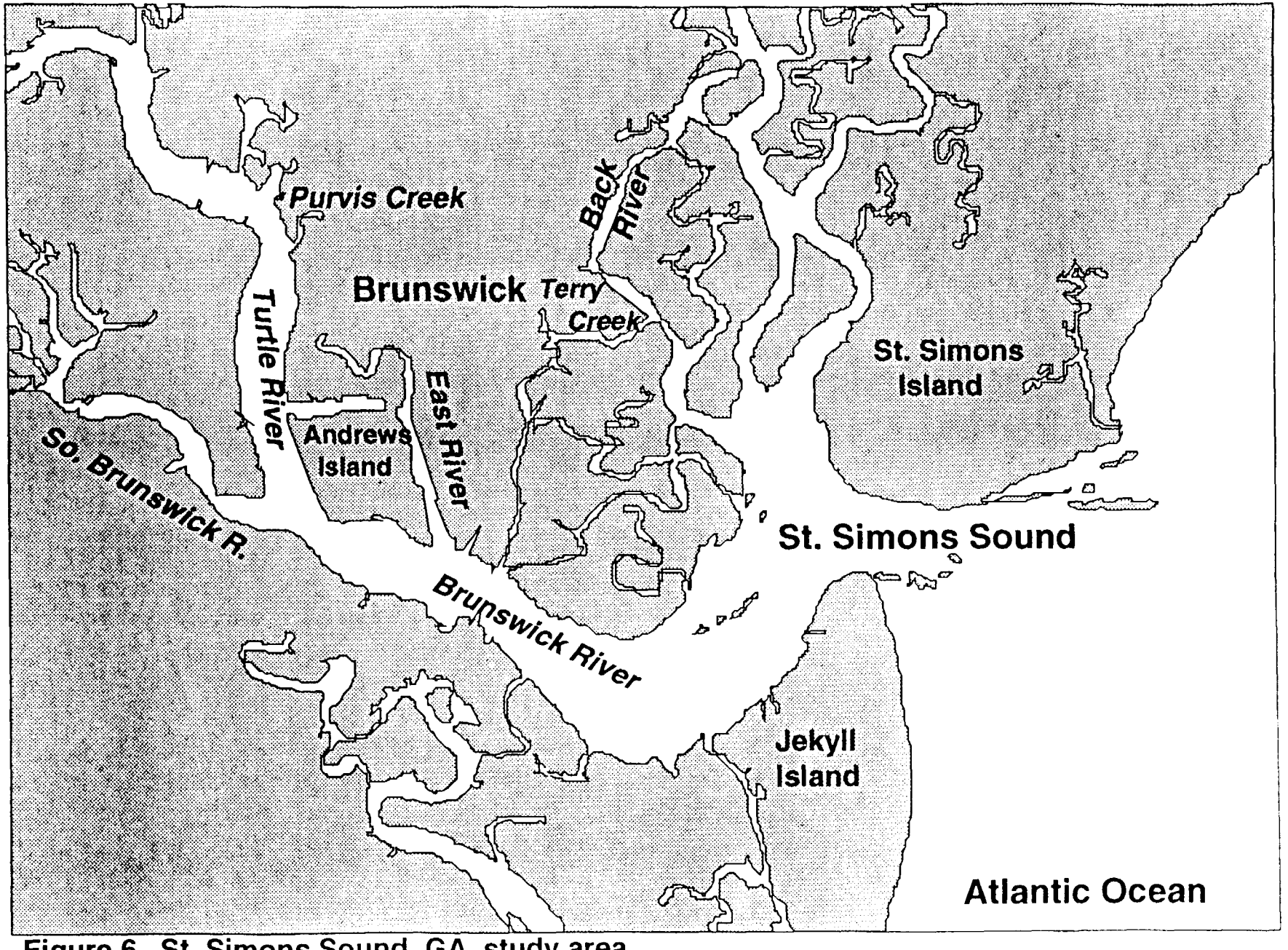


Figure 6. St. Simons Sound, GA, study area.

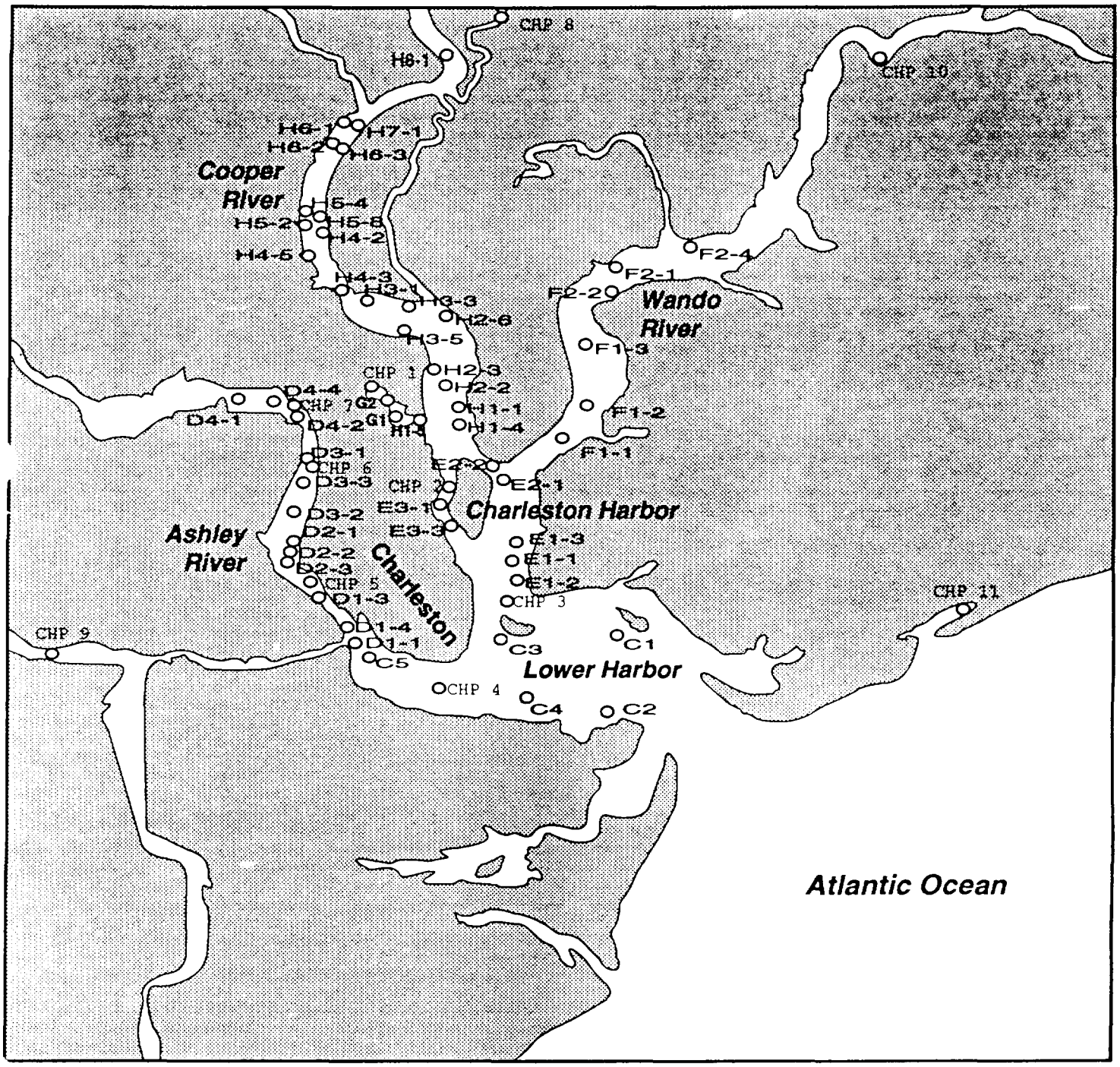


Figure 7. Locations of sampling stations in Charleston Harbor.

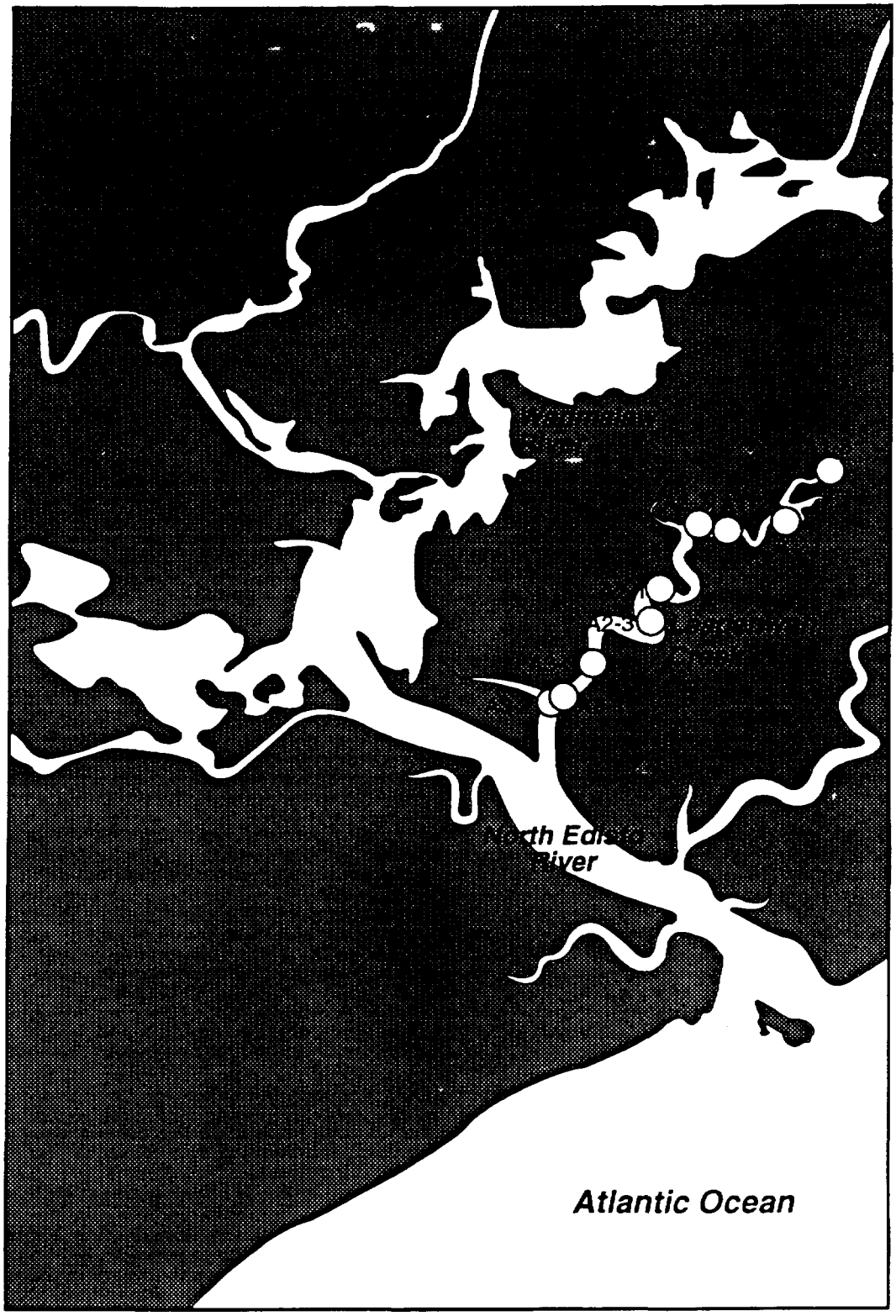


Figure 8. Locations of sampling stations in Leadenwah Creek.

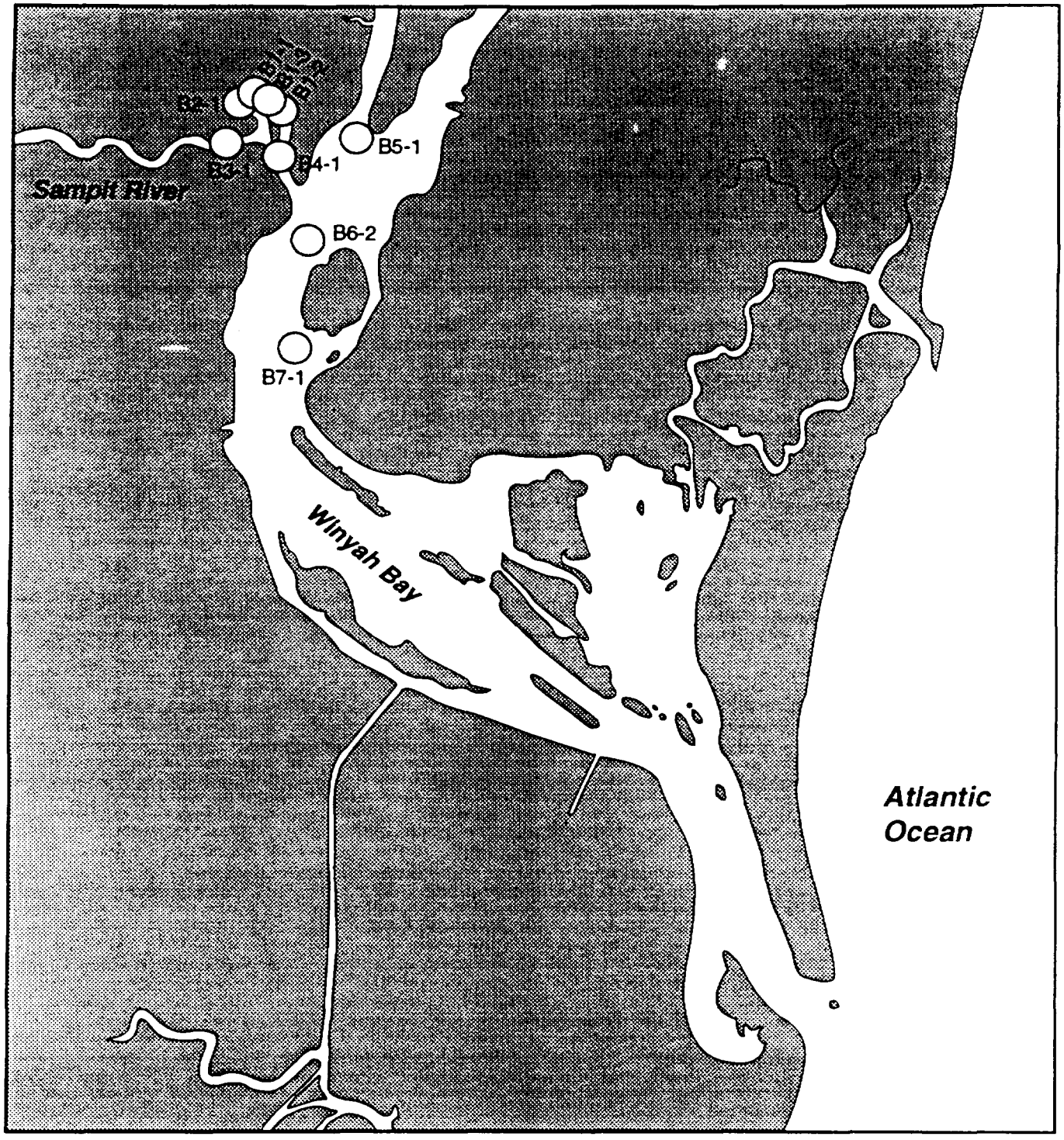


Figure 9. Locations of sampling stations in Winyah Bay.

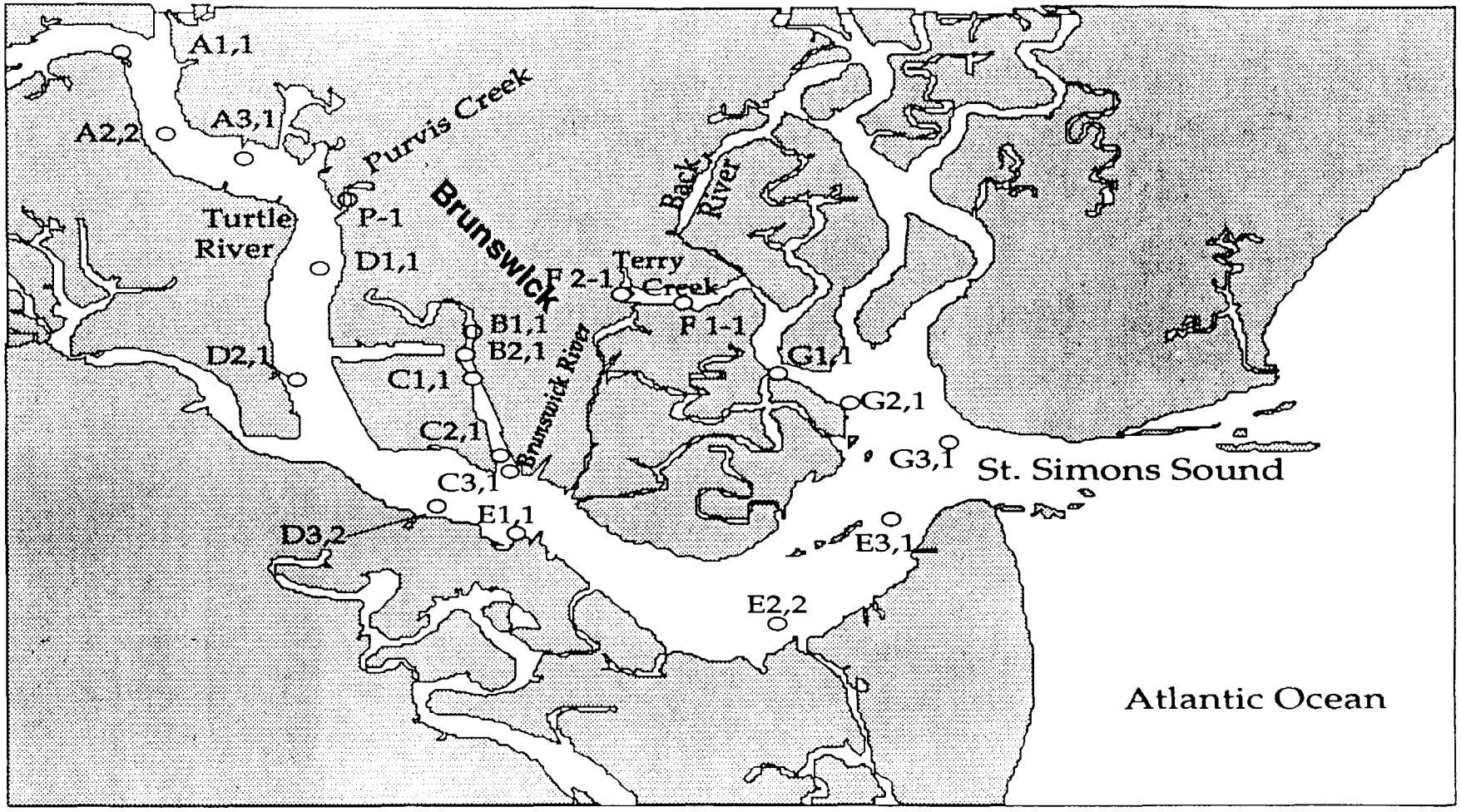


Figure 10. Locations of sampling stations in St. Simons Sound.

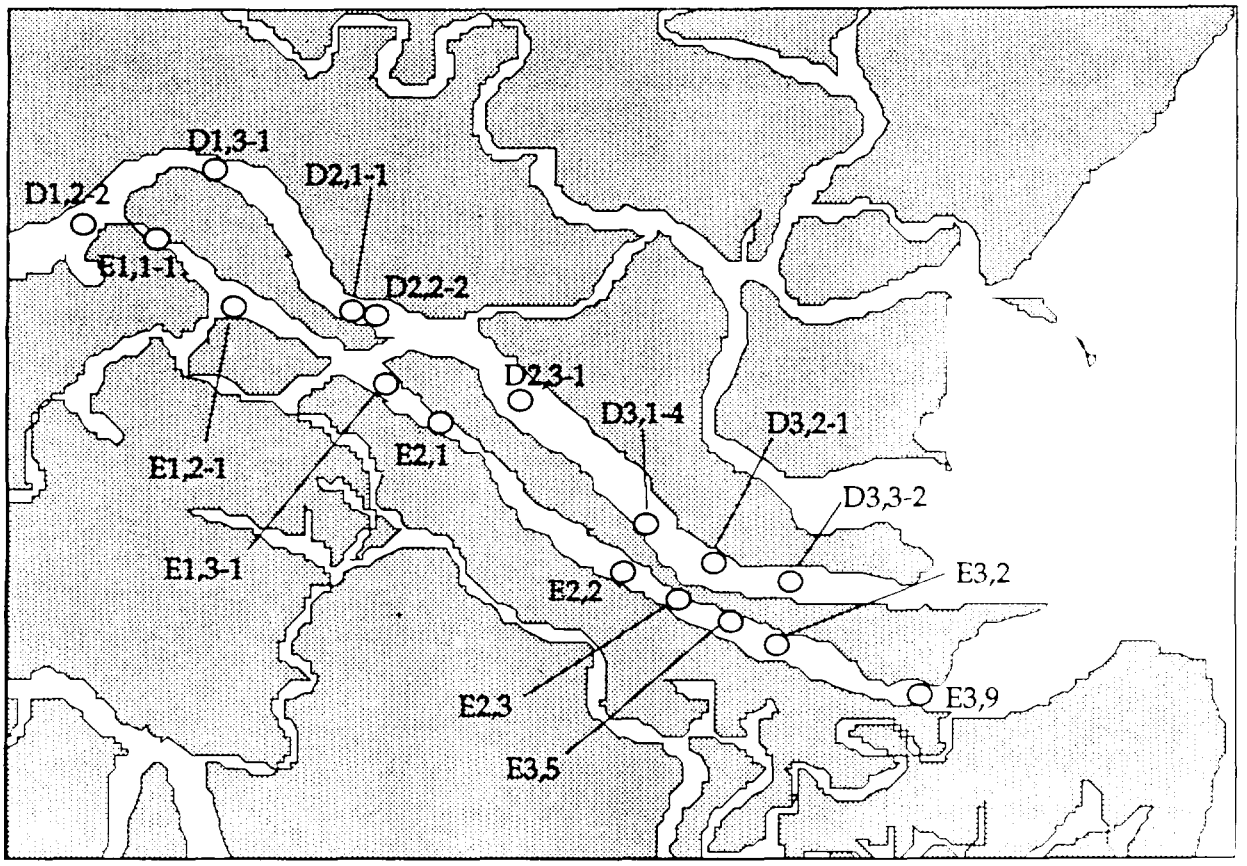


Figure 11. Locations of sampling stations in the lower Savannah River.

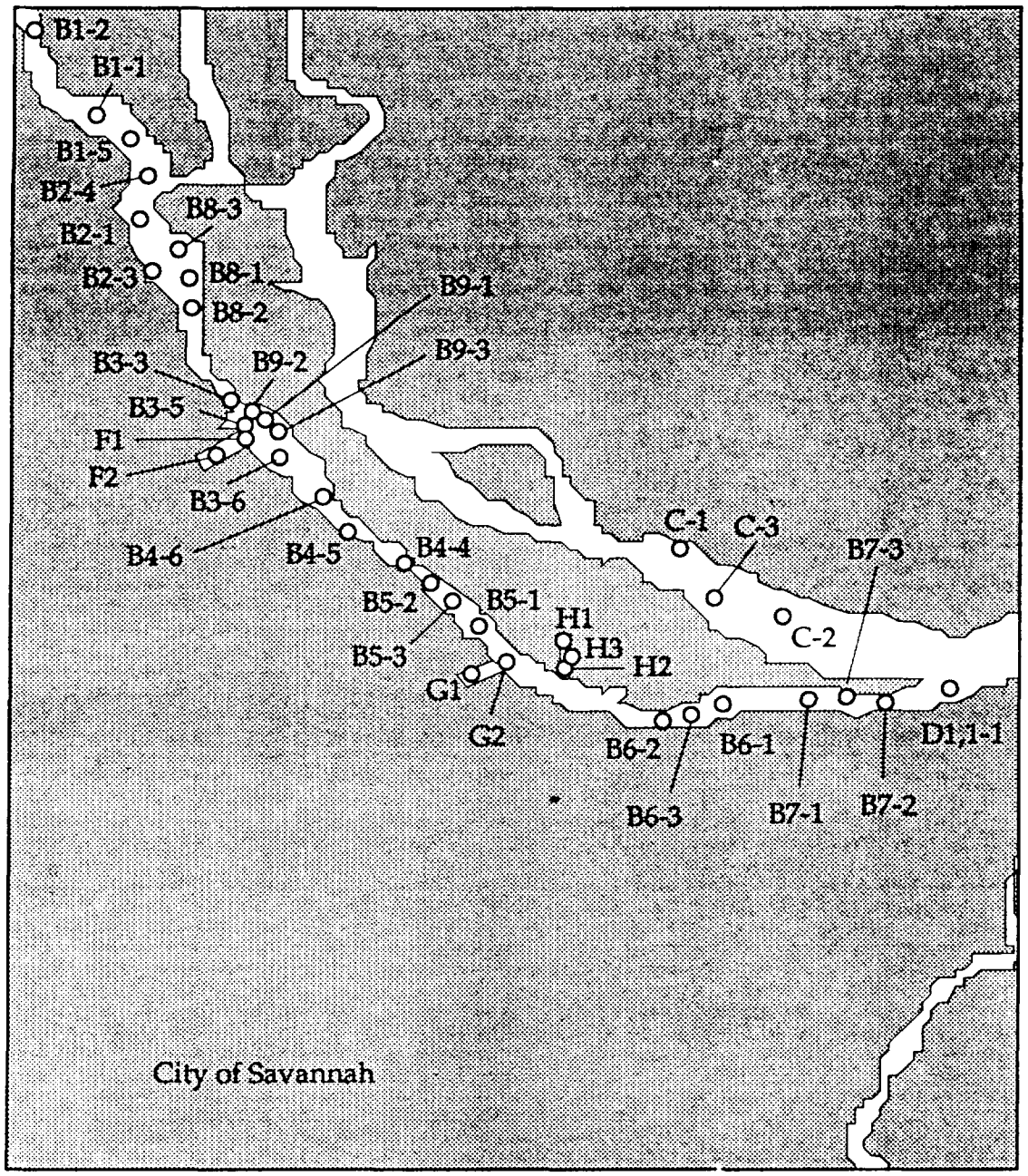


Figure 12. Locations of sampling stations in the mid-Savannah River.

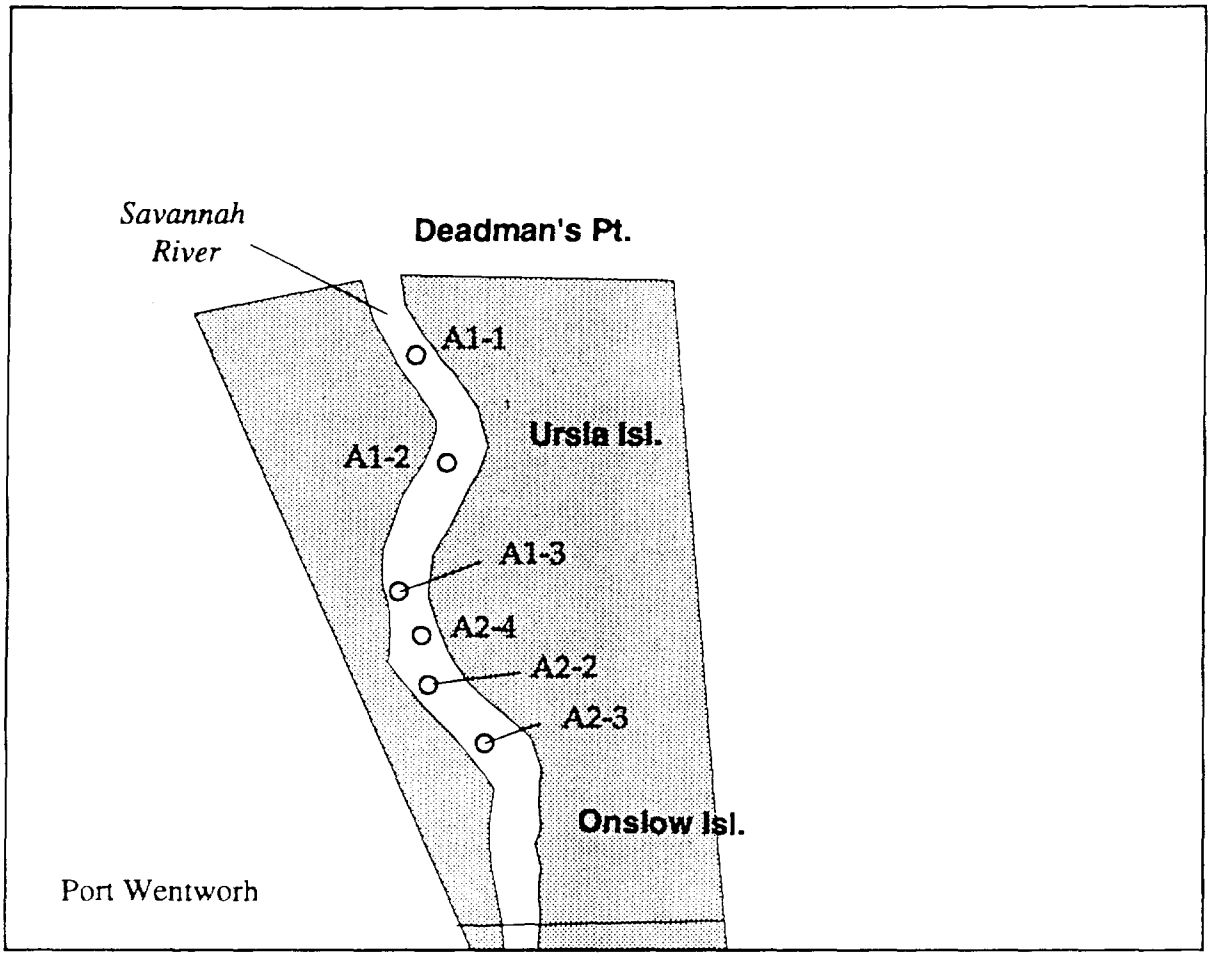


Figure 13. Locations of sampling stations in the upper Savannah River.

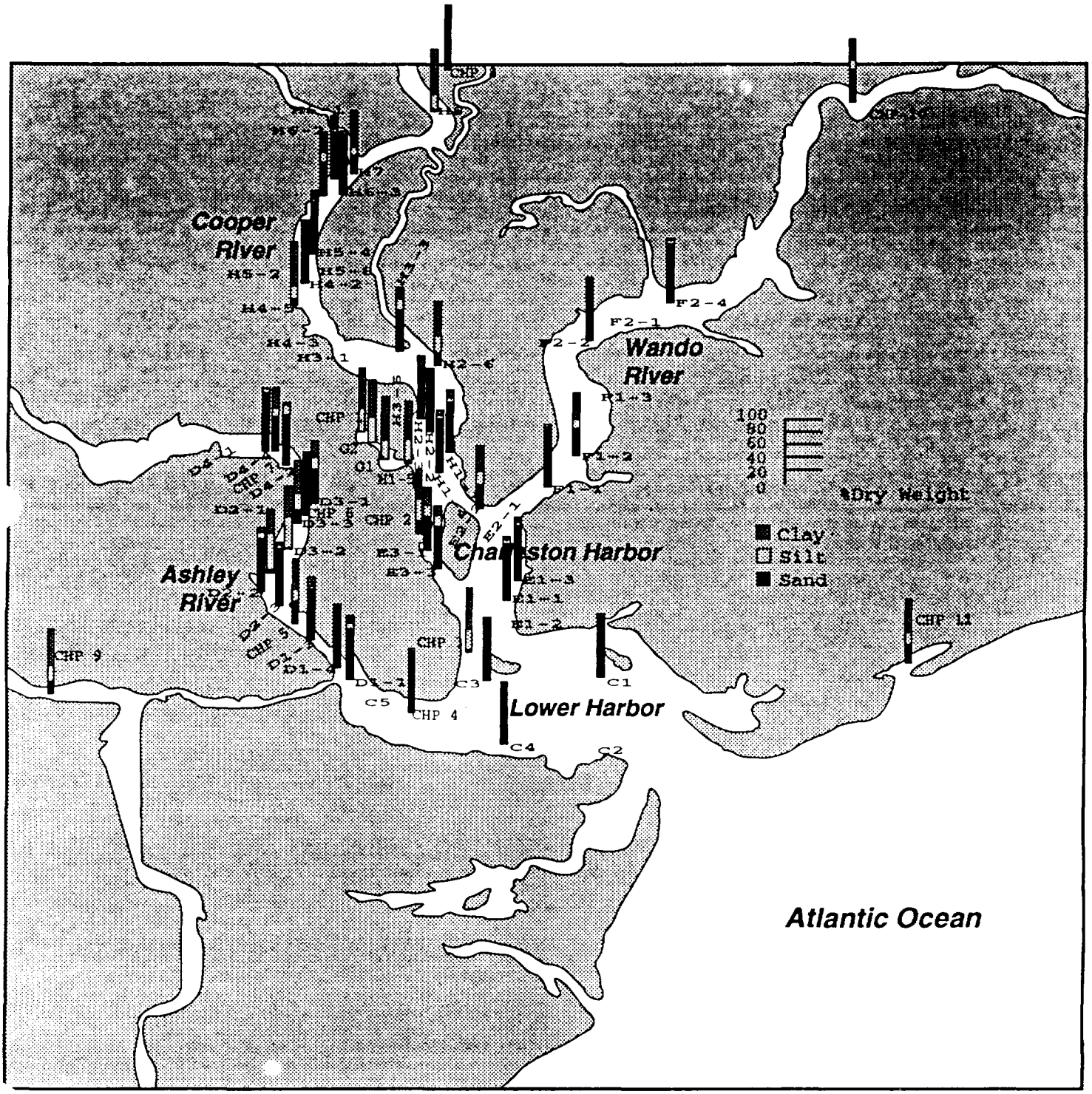


Figure 14. Percent sand, silt, and clay in sediment samples from Charleston Harbor.

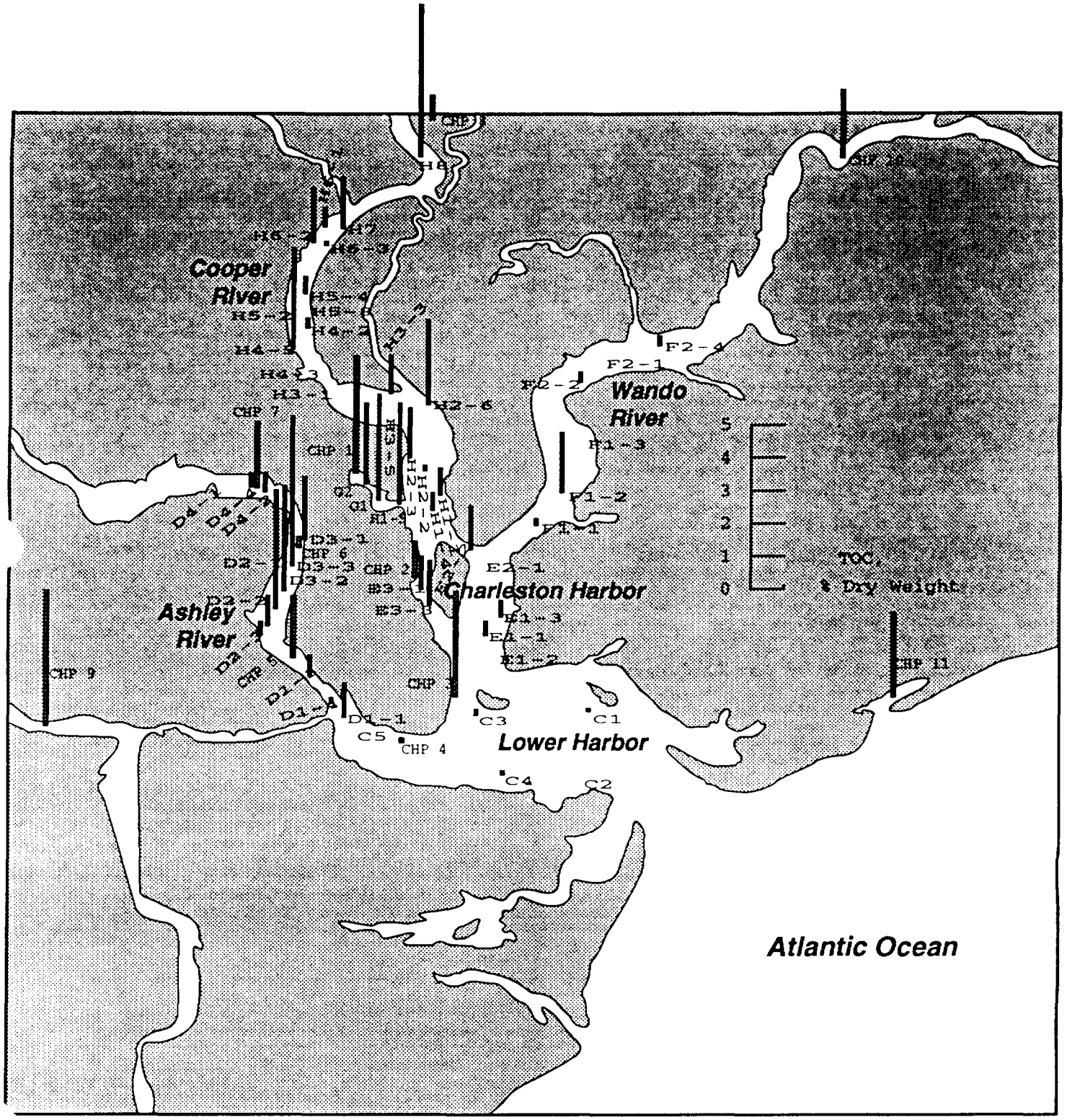
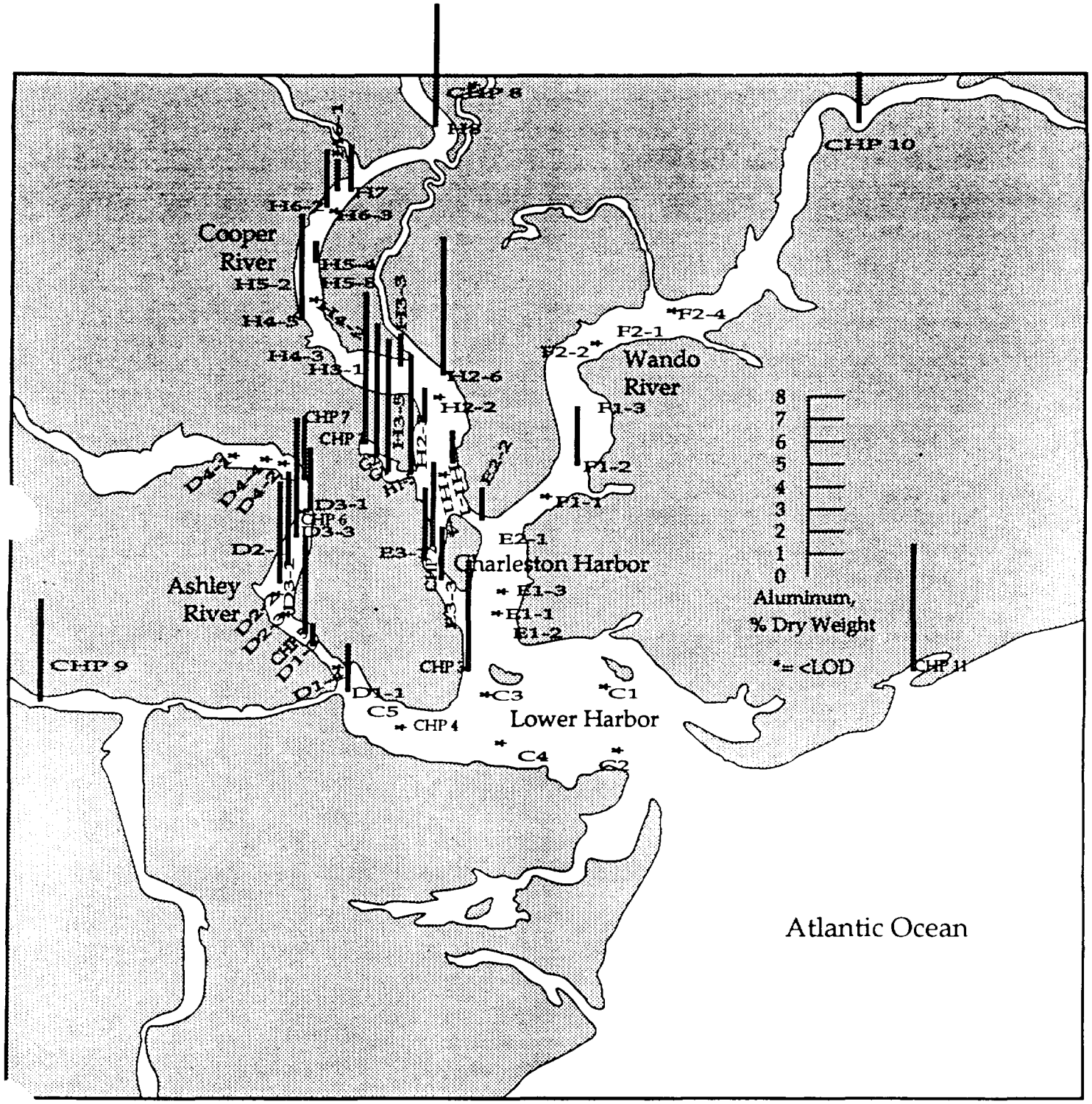


Figure 15. Concentrations of total organic carbon in sediments from Charleston Harbor.



. igure 16. **Concentrations of aluminum in sediments from Charleston Harbor.**

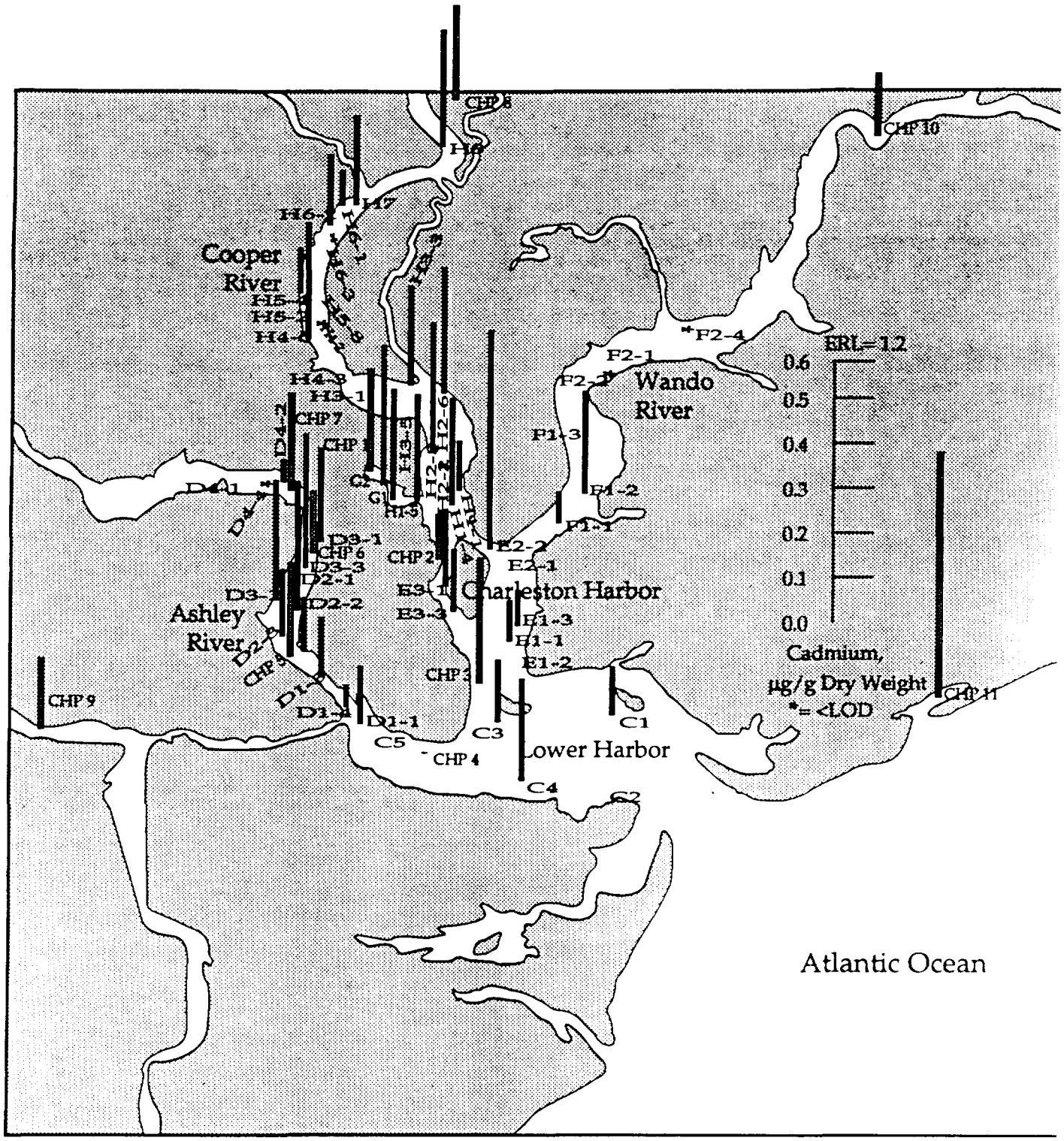


Figure 18. Concentrations of cadmium in sediments from Charleston Harbor.

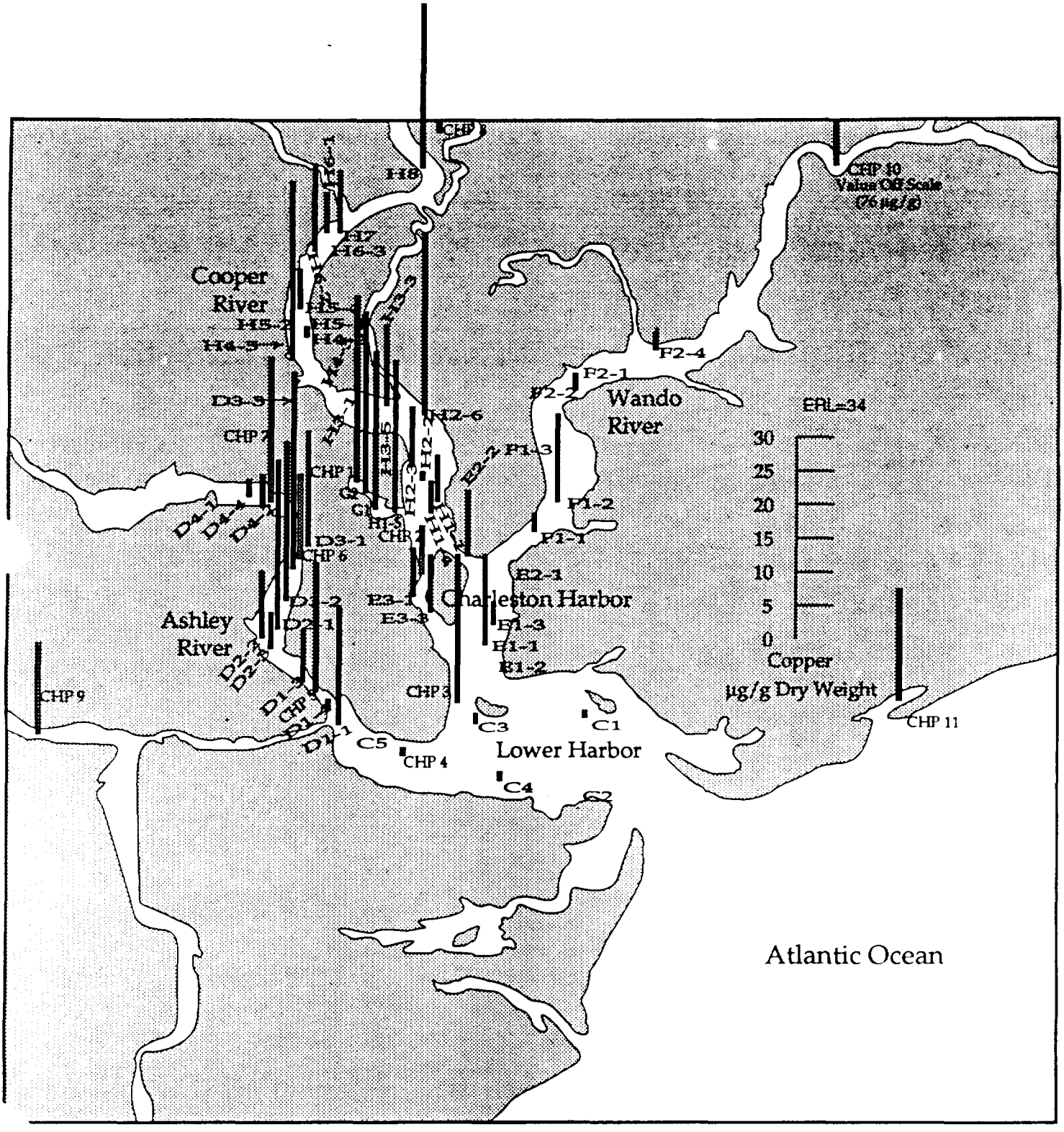


Figure 19. Concentrations of copper in sediments from Charleston Harbor.

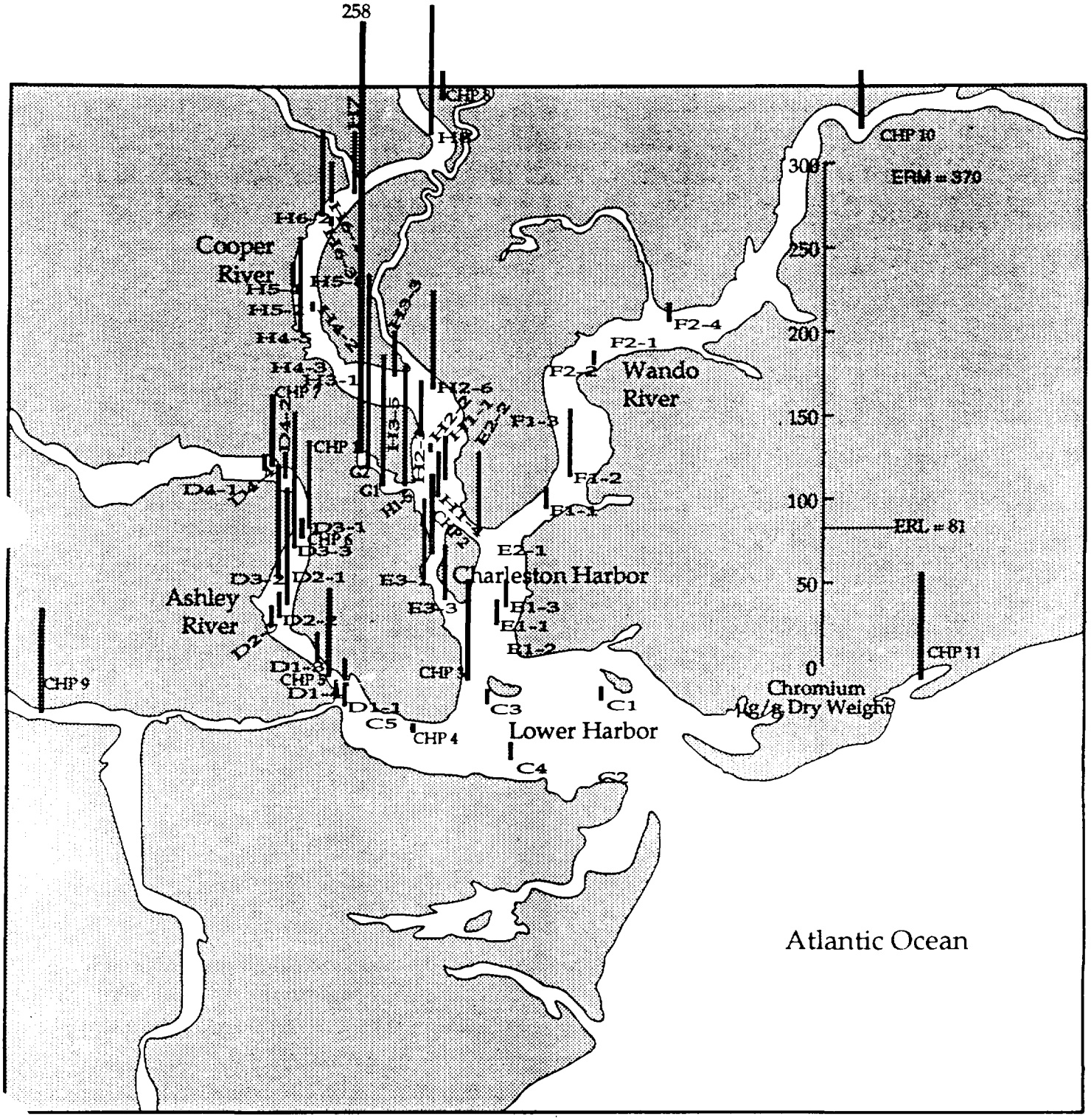


Figure 20. Concentrations of chromium in sediments from Charleston Harbor.

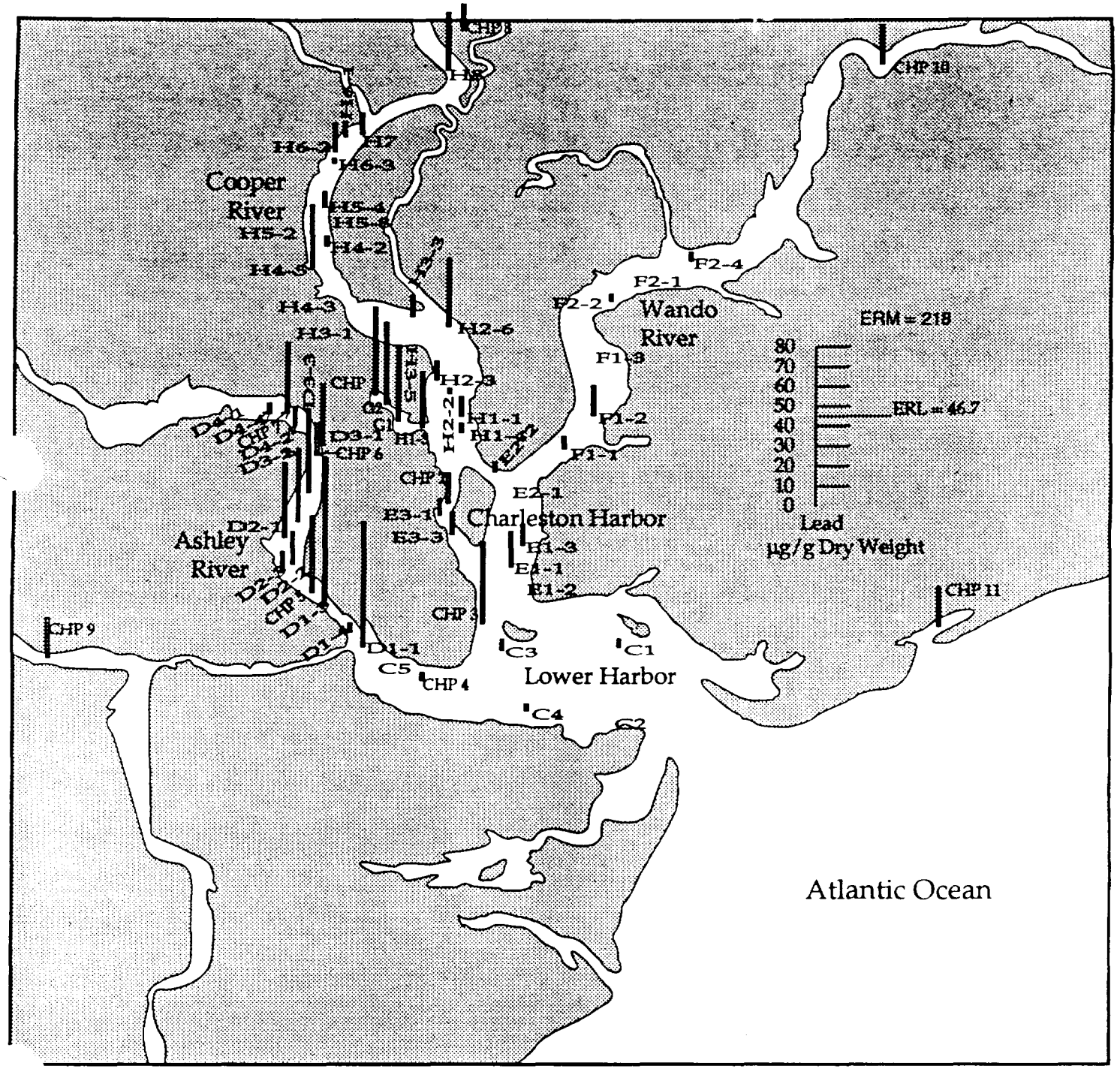


Figure 21. Concentrations of lead in sediments from Charleston Harbor.

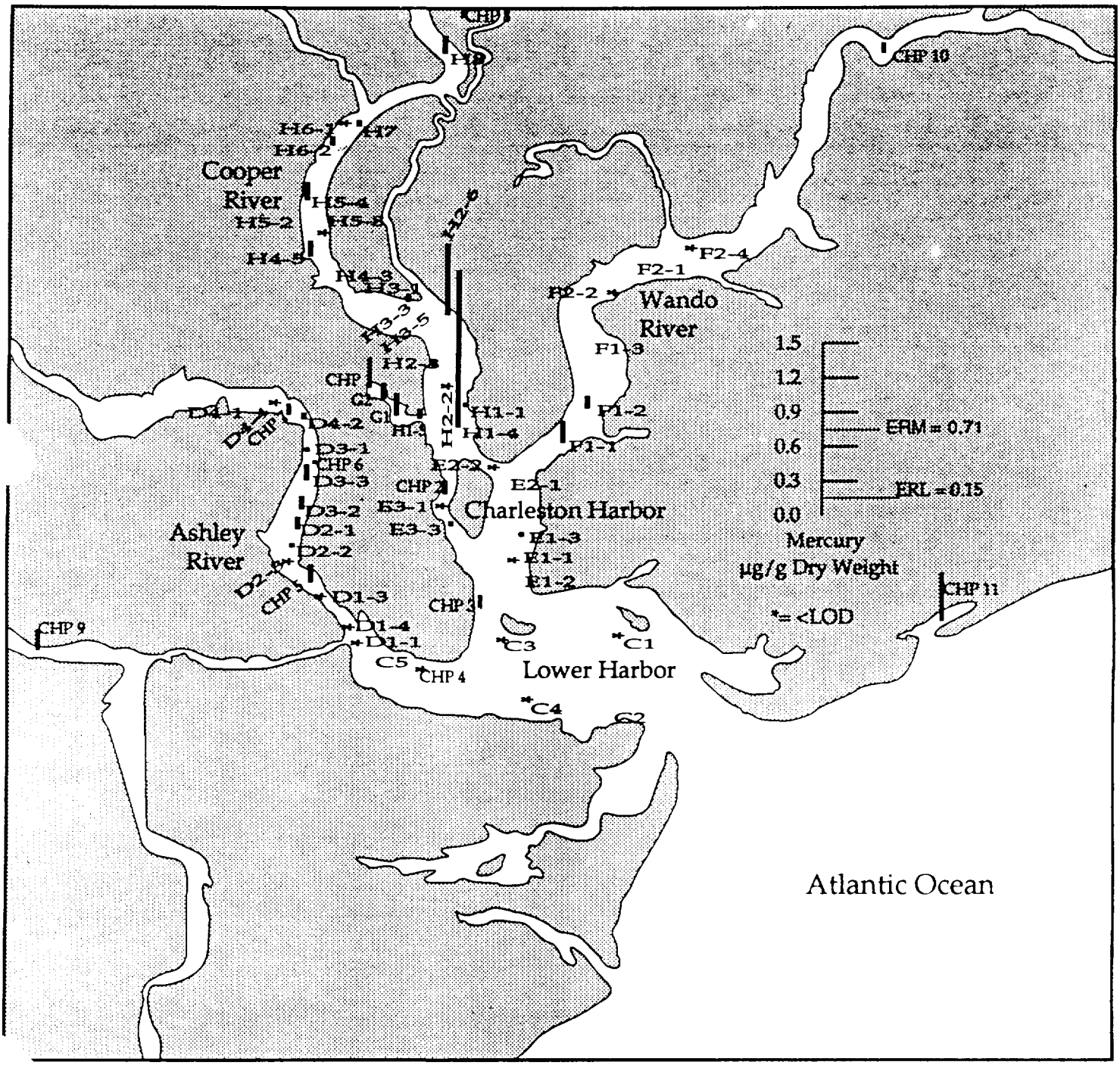


Figure 22. Concentrations of mercury in sediments from Charleston Harbor.

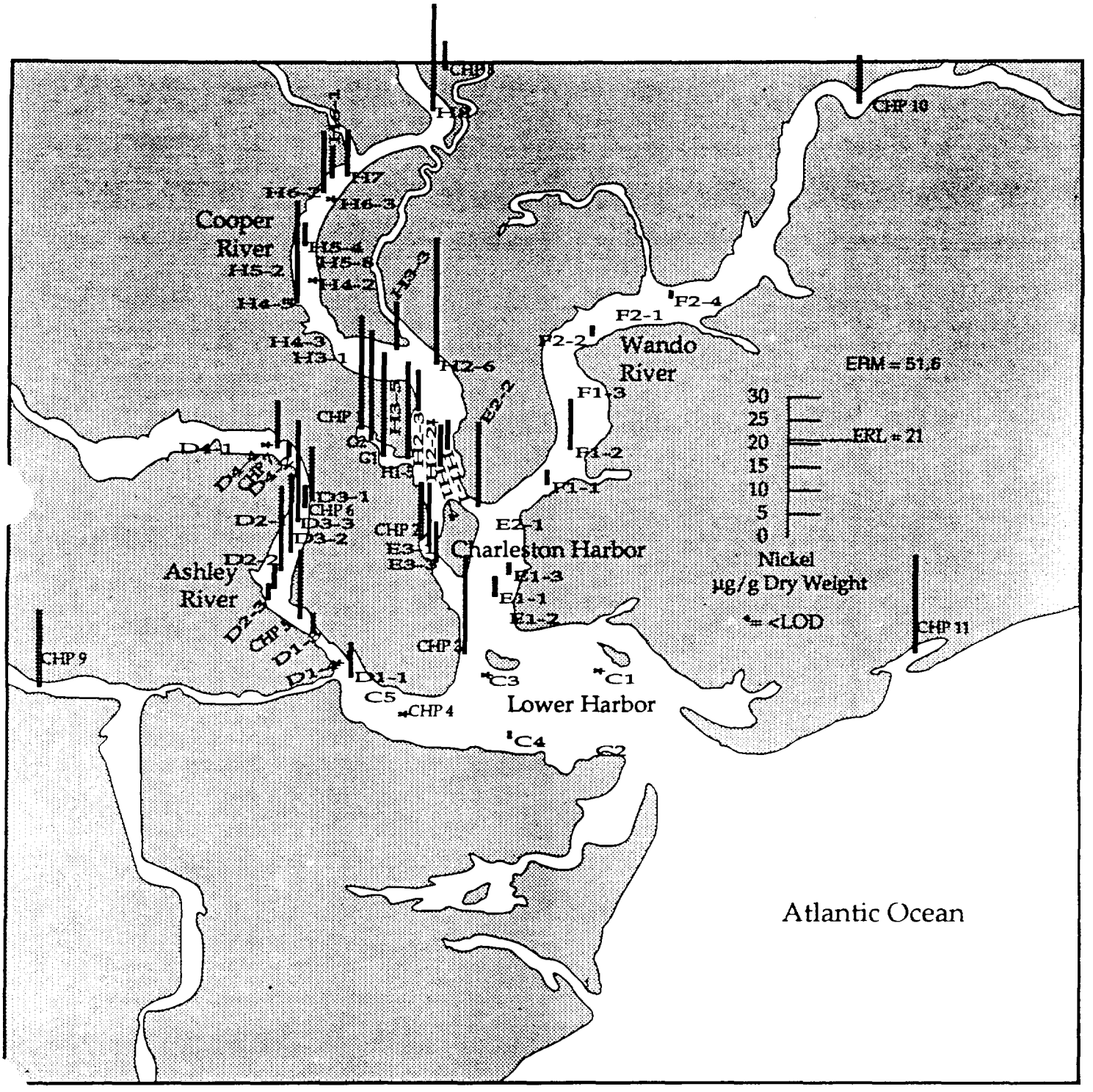


Figure 23. Concentrations of nickel in sediments from Charleston Harbor.

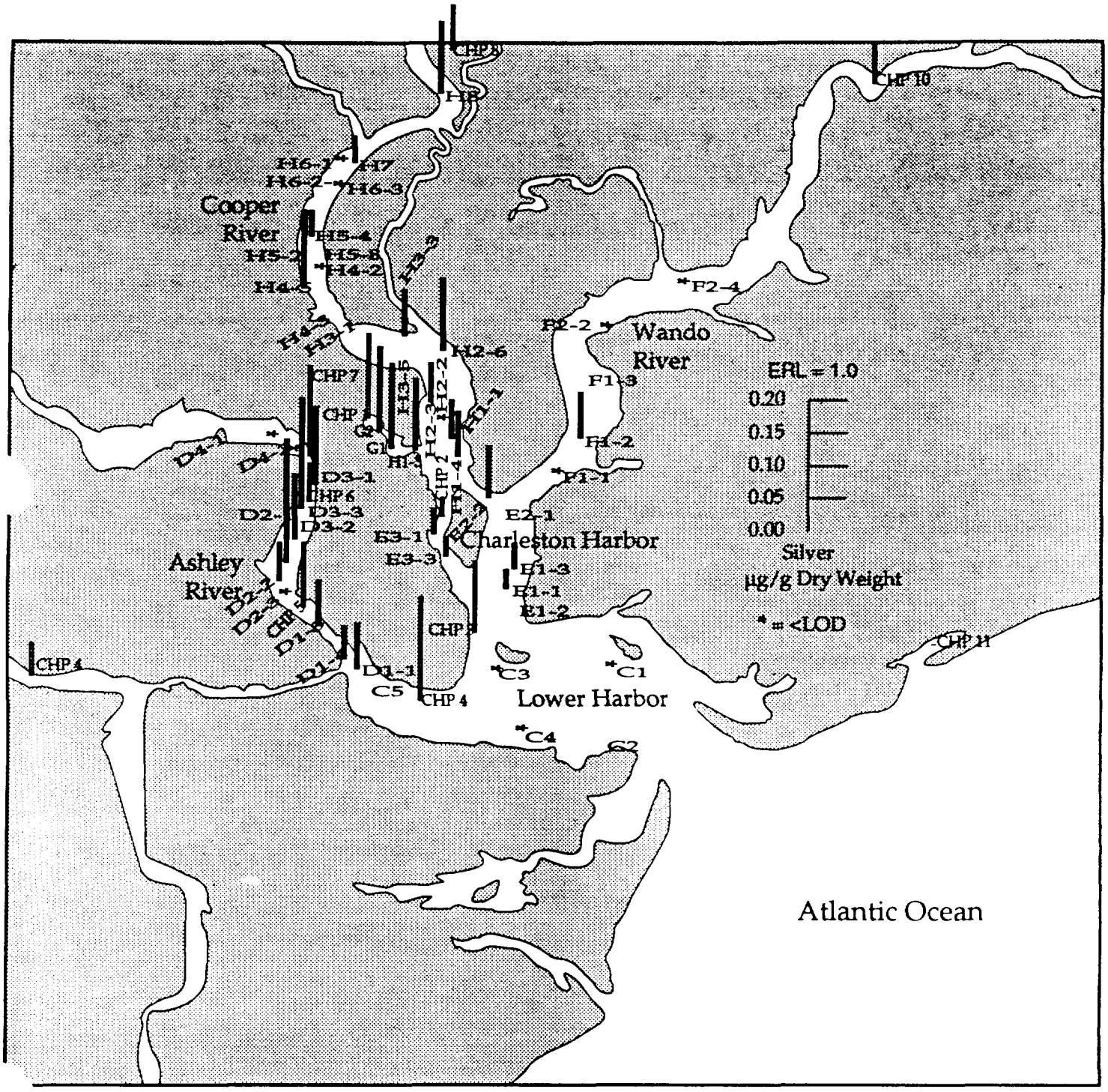


Figure 24. Concentrations of silver in sediments from Charleston Harbor.

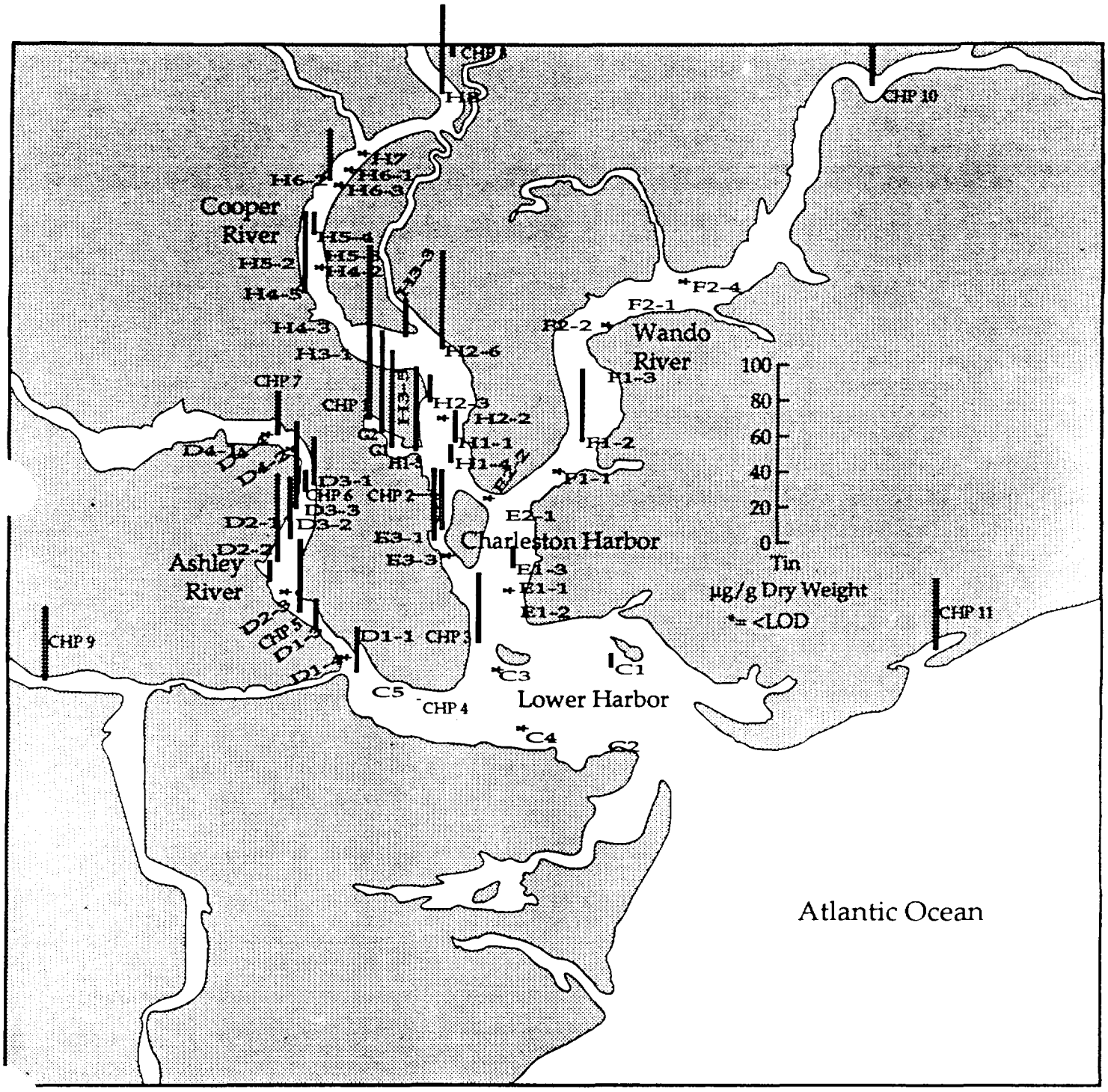


Figure 25. Concentrations of tin in sediments from Charleston Harbor.

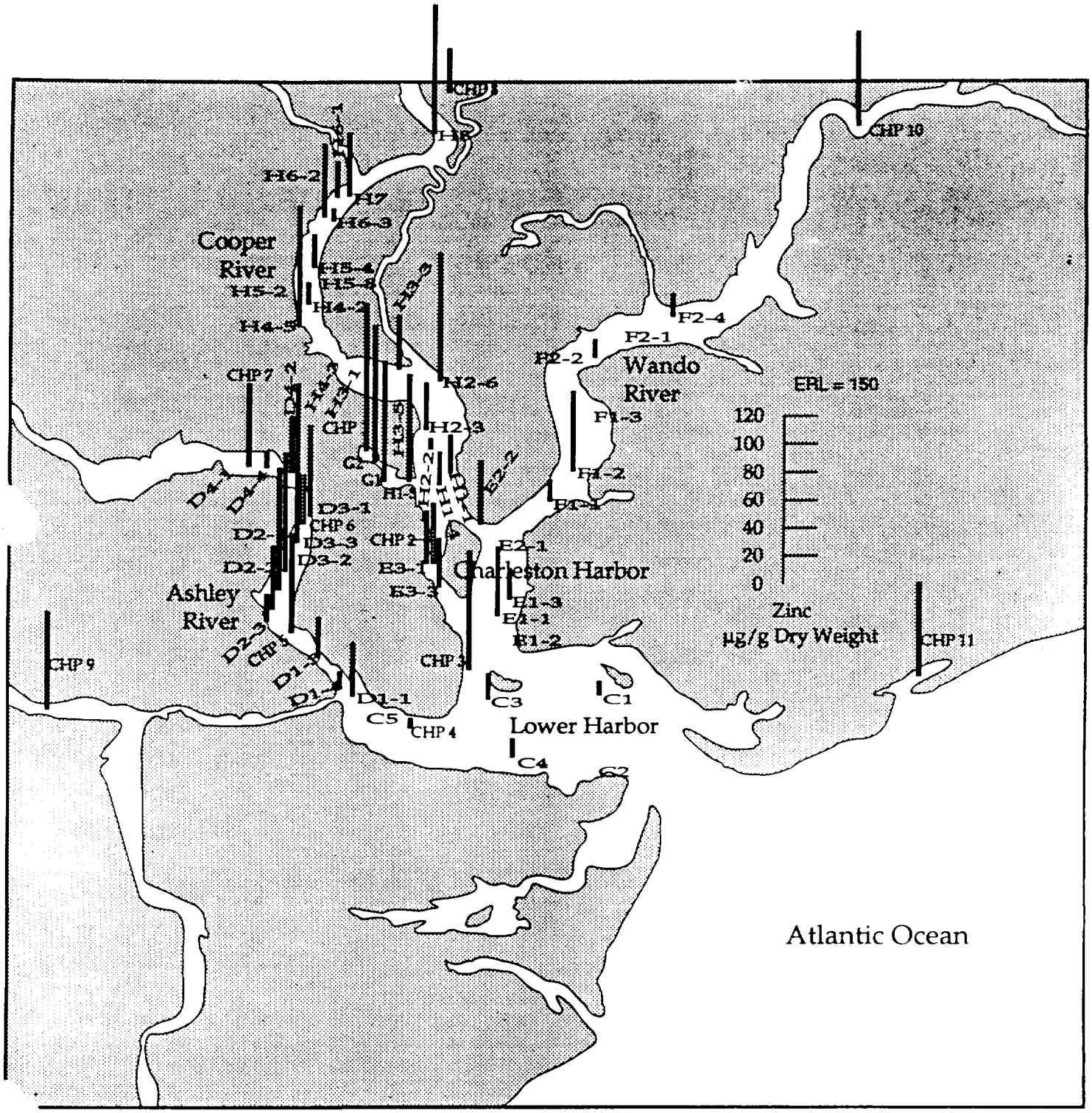


Figure 26. Concentrations of zinc in sediments from Charleston Harbor.

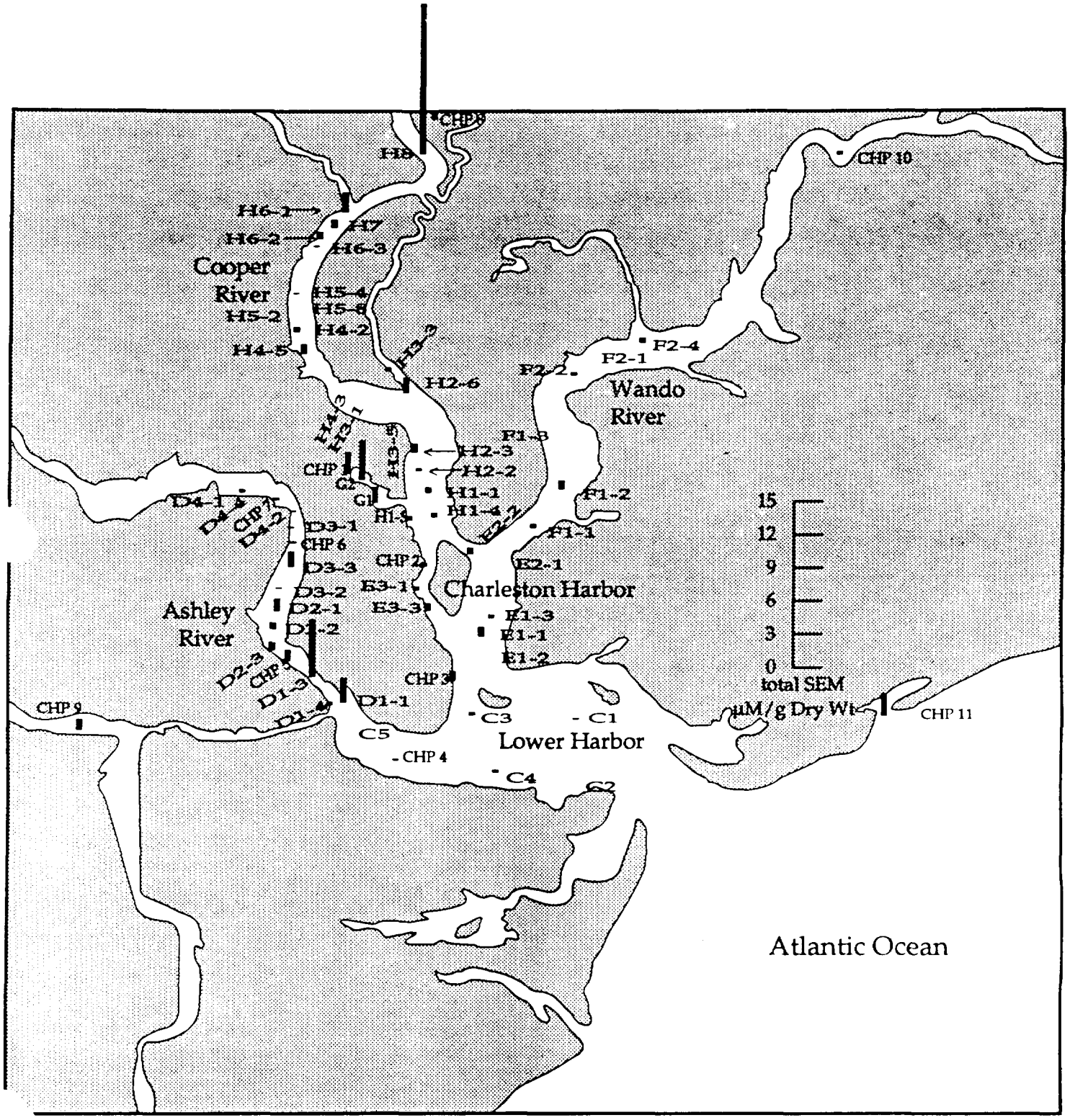


Figure 27. Concentrations of total simultaneously-extracted divalent metals in sediments from Charleston Harbor.

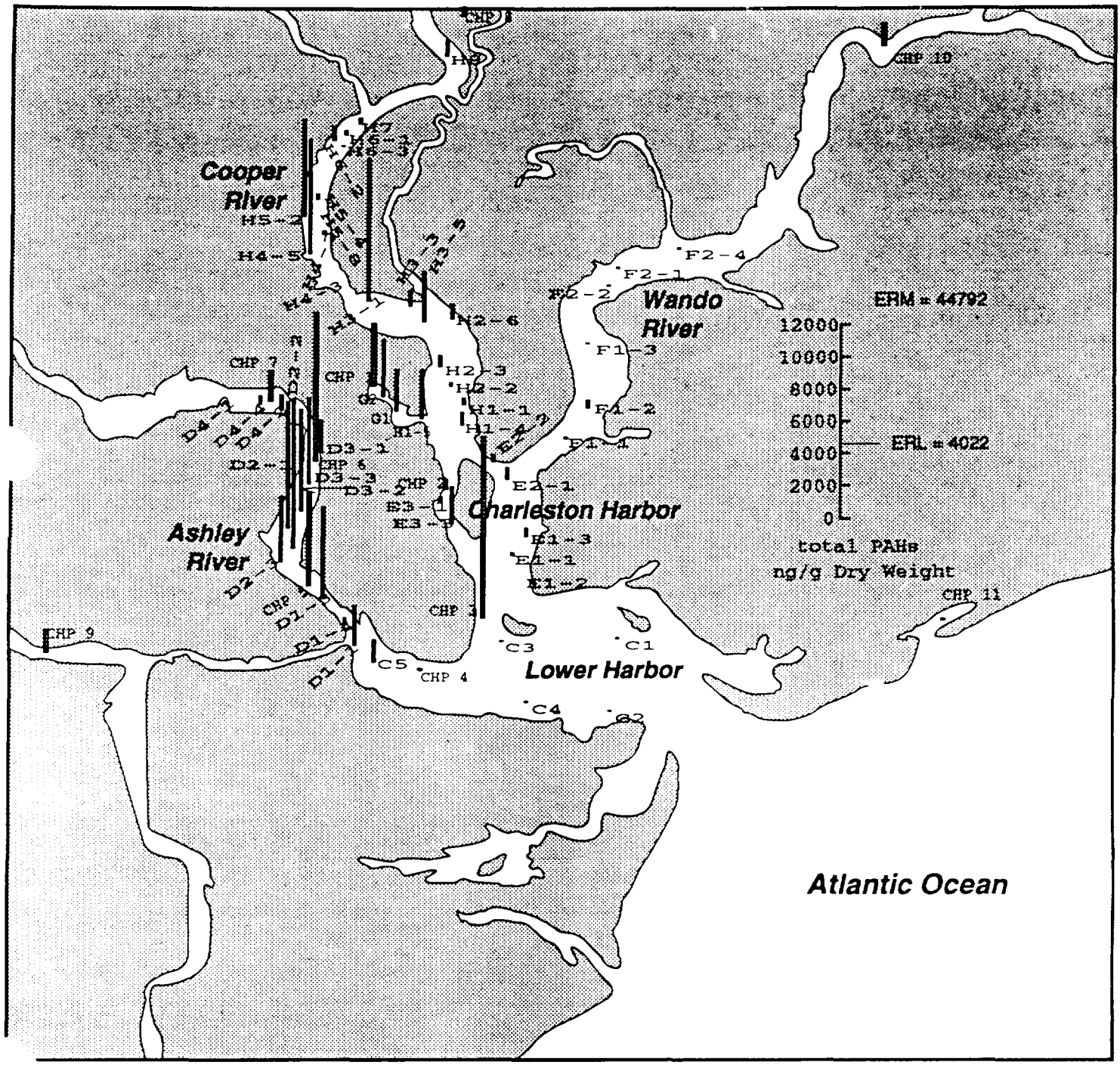


Figure 28. Concentrations of total PAHs in sediments from Charleston Harbor.

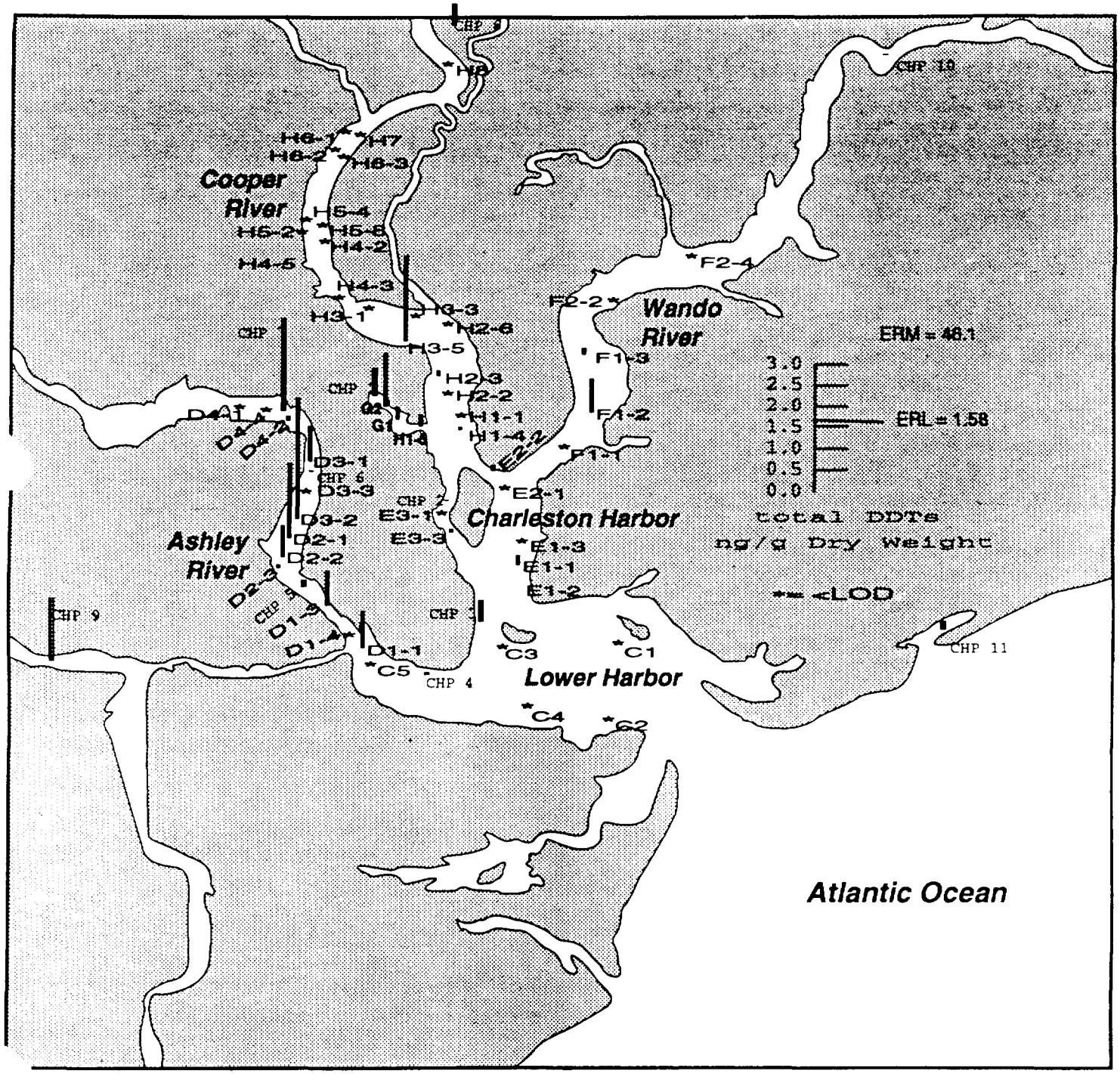


Figure 29. Concentrations of total DDTs in sediments from Charleston Harbor.

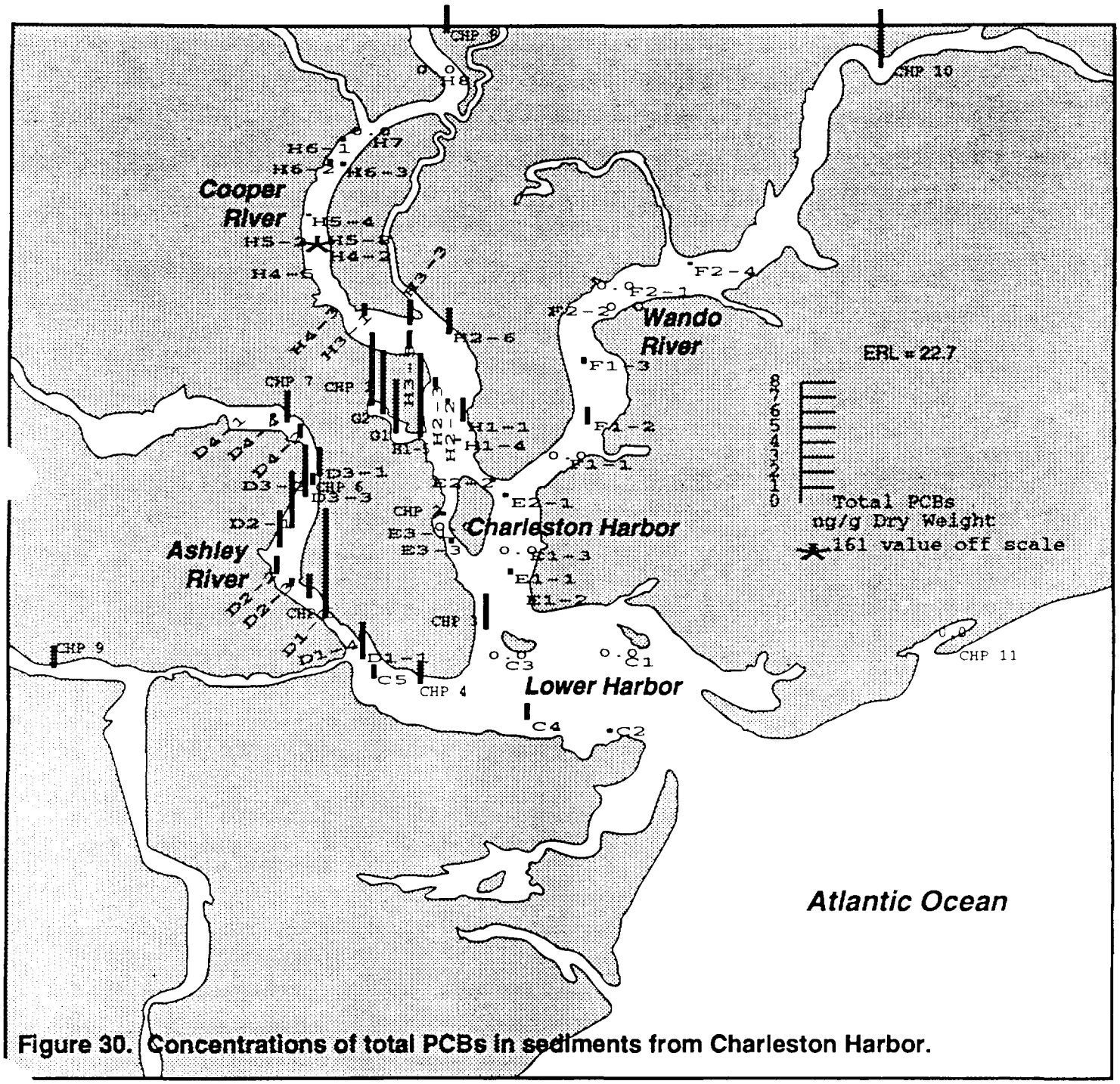


Figure 30. Concentrations of total PCBs in sediments from Charleston Harbor.

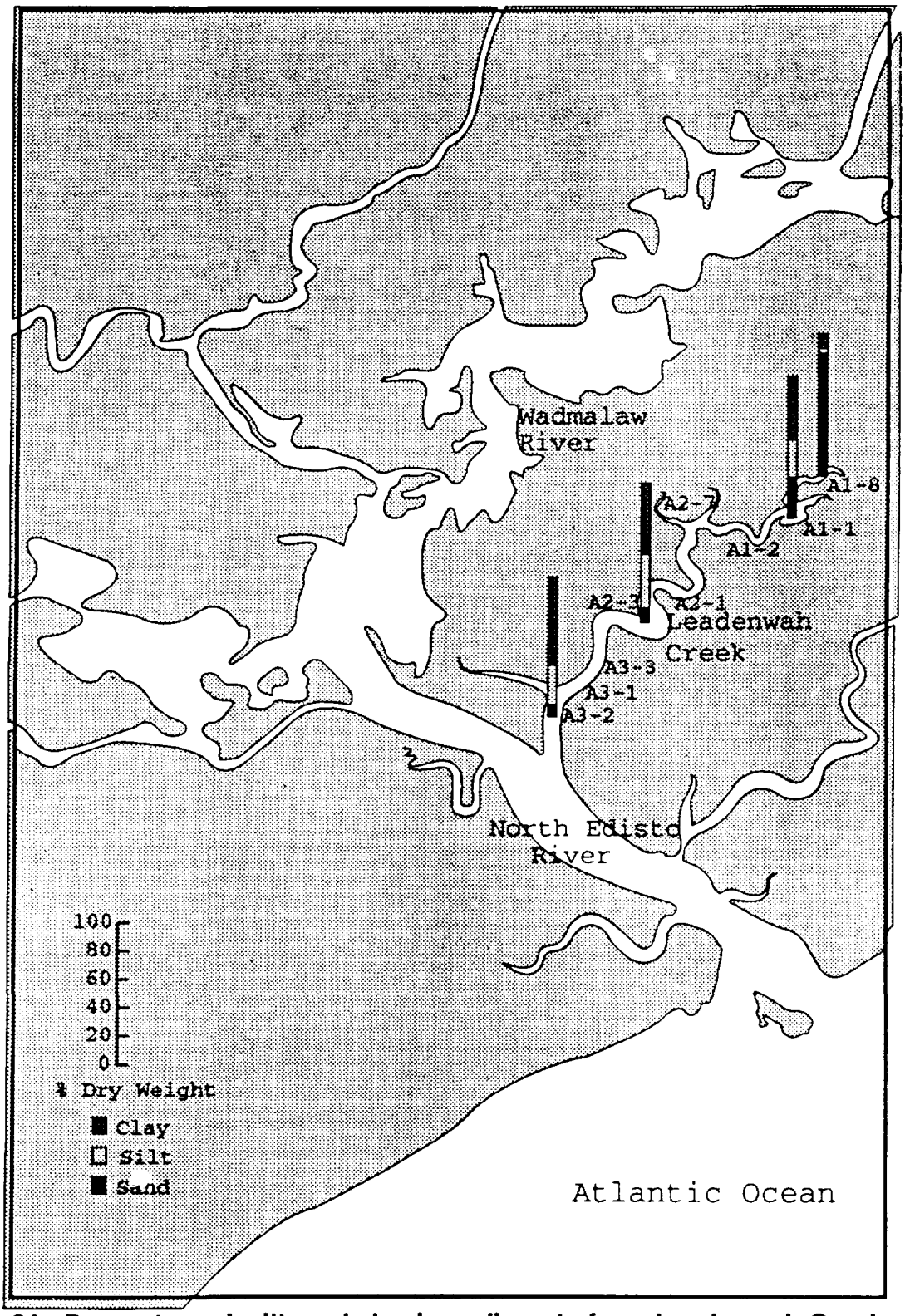


Figure 31. Percent sand, silt, and clay in sediments from Leadenwah Creek.

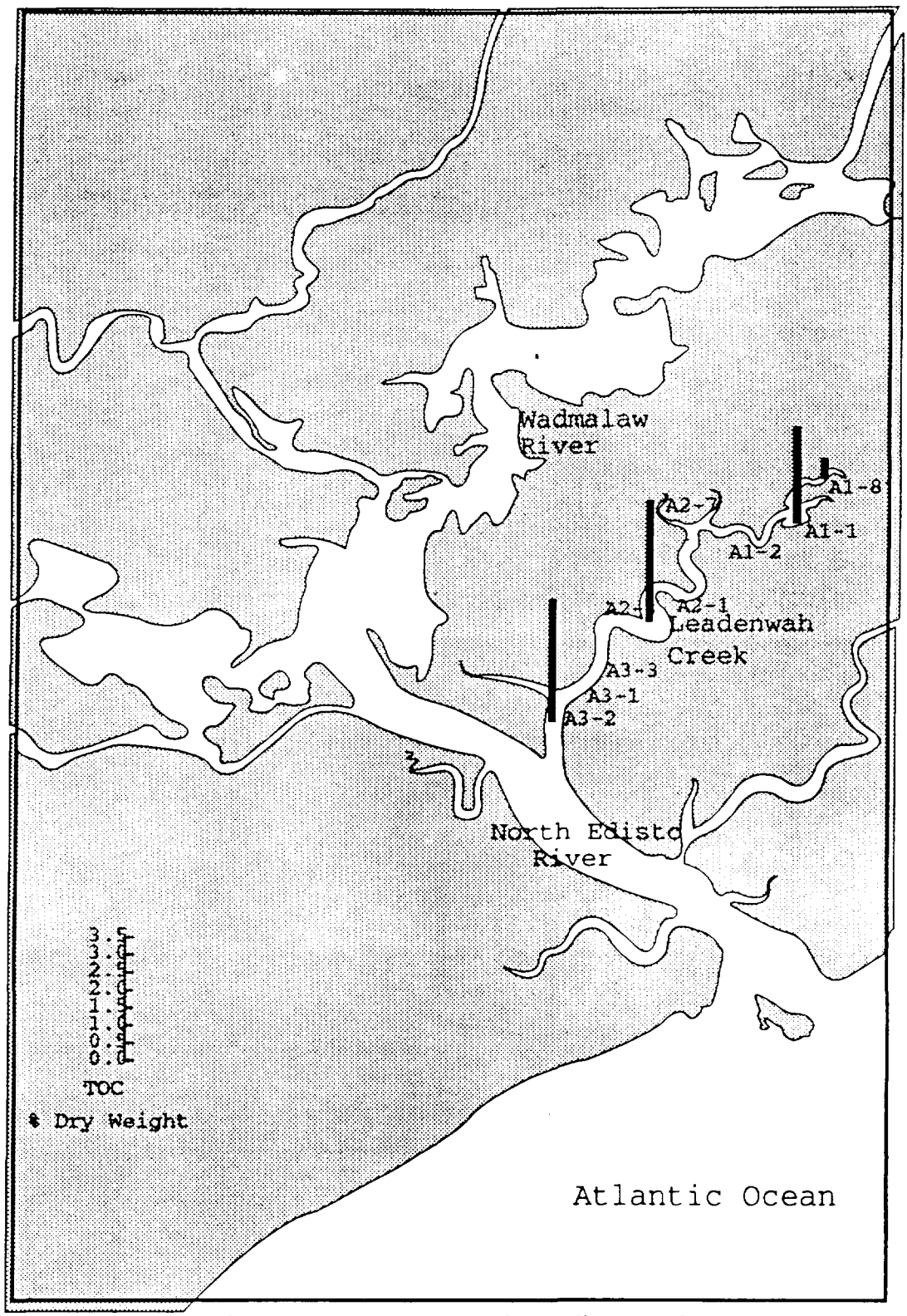


Figure 32. Concentrations of total organic carbon in sediments from Leadenwah Creek.

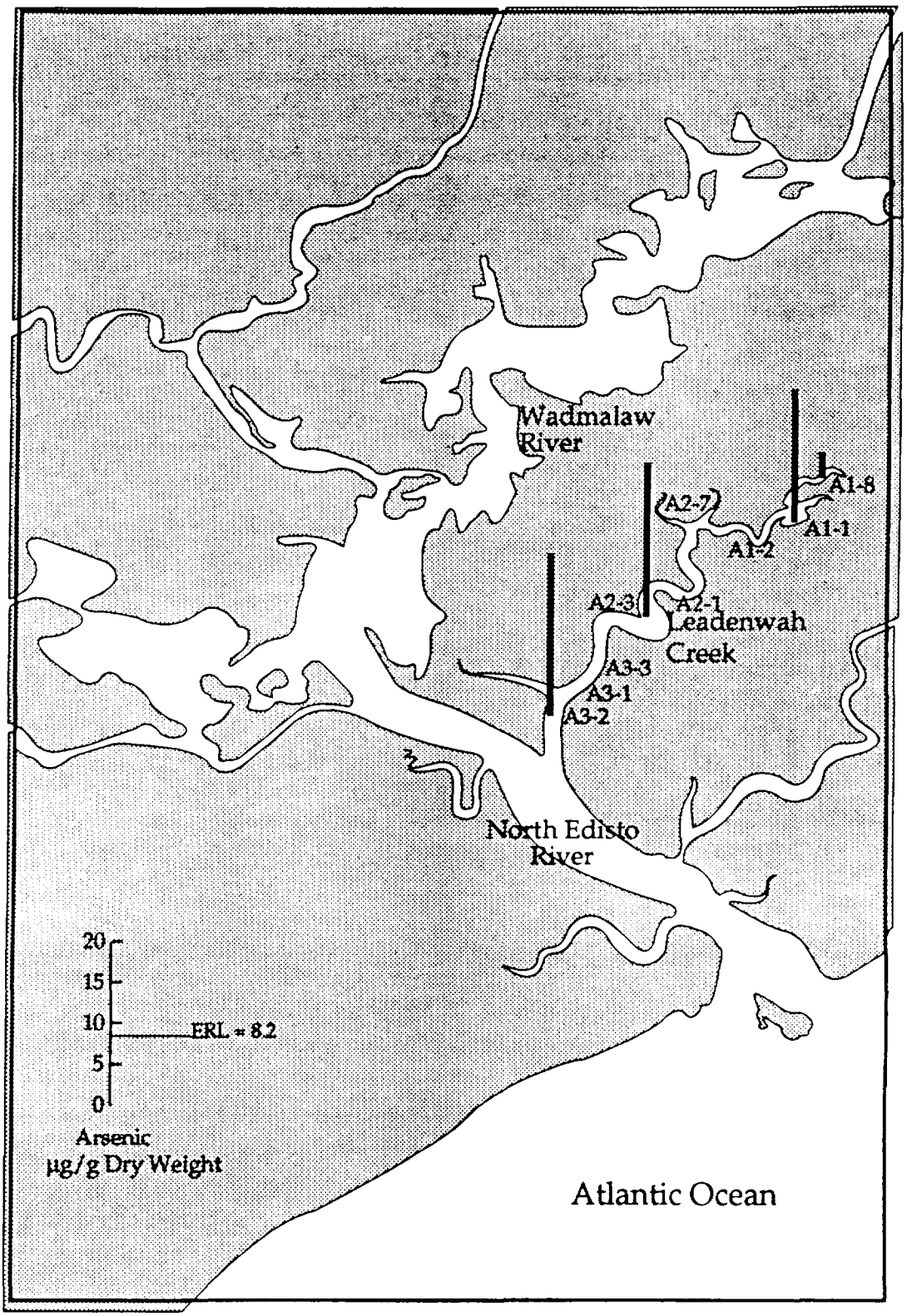


Figure 33. Concentrations of arsenic in sediments from Leadenwah Creek.

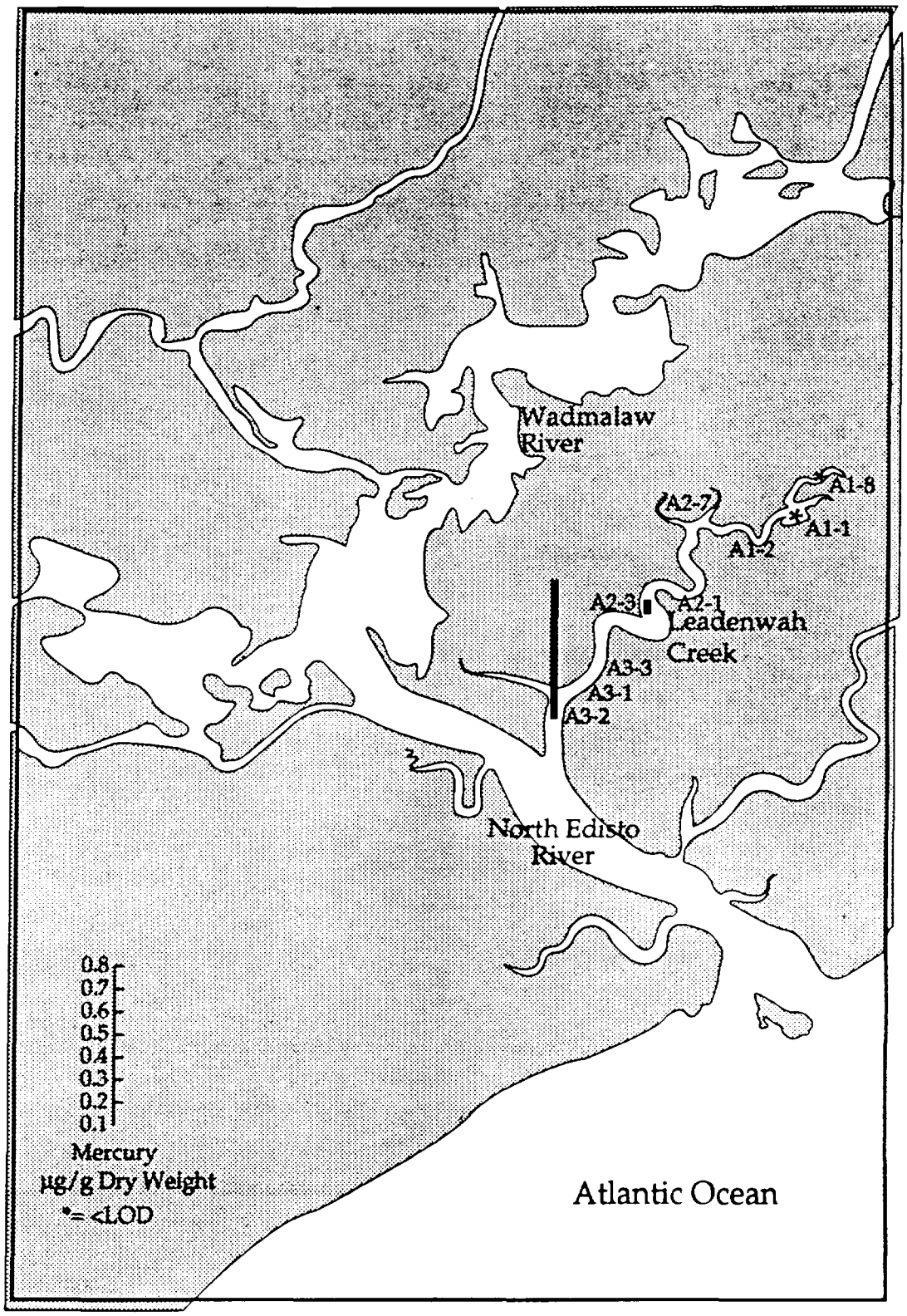


Figure 34. Concentrations of mercury in sediments from Leadenwah Creek.

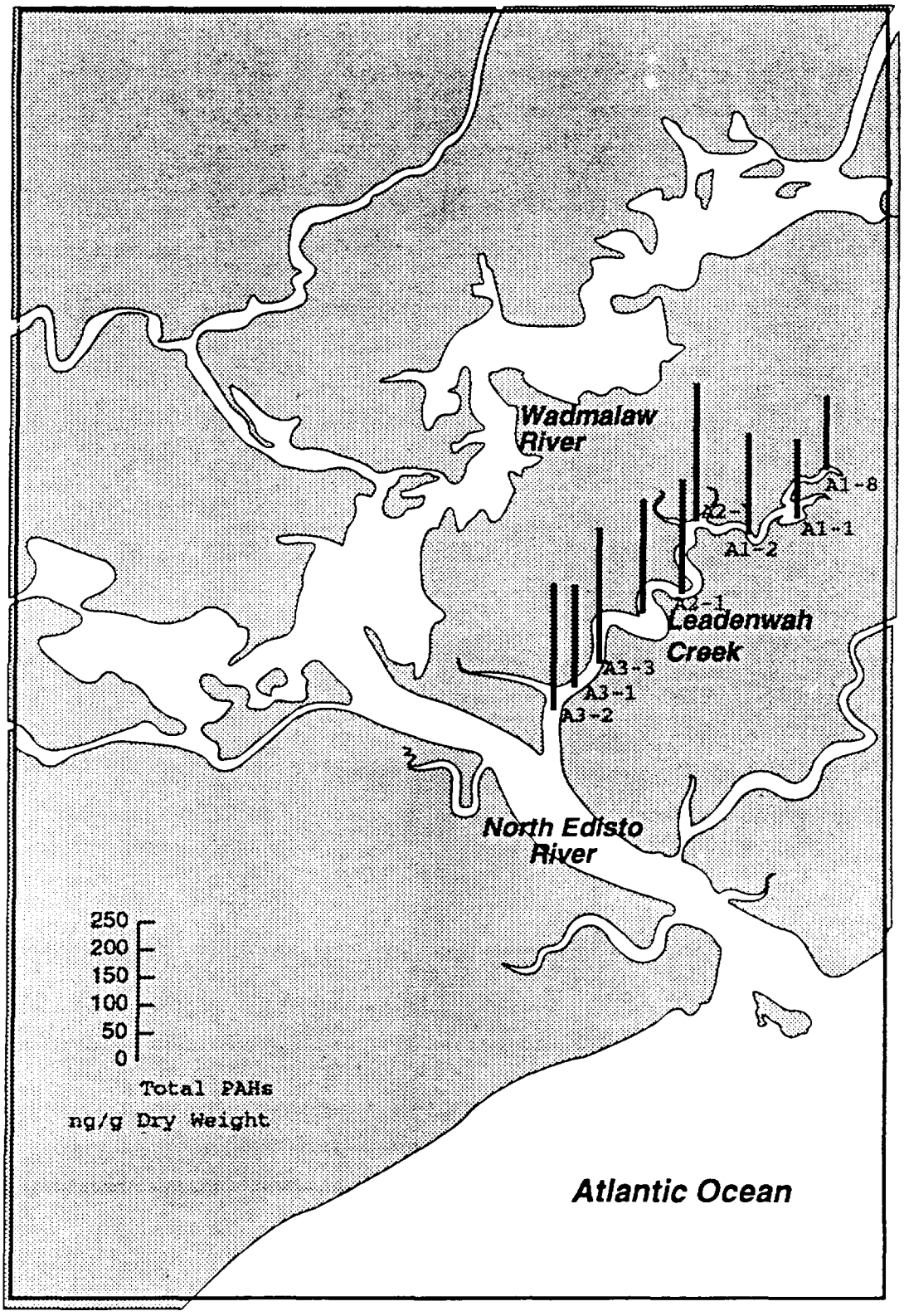


Figure 35. Concentrations of total PAHs in sediments from Leadenwah Creek.

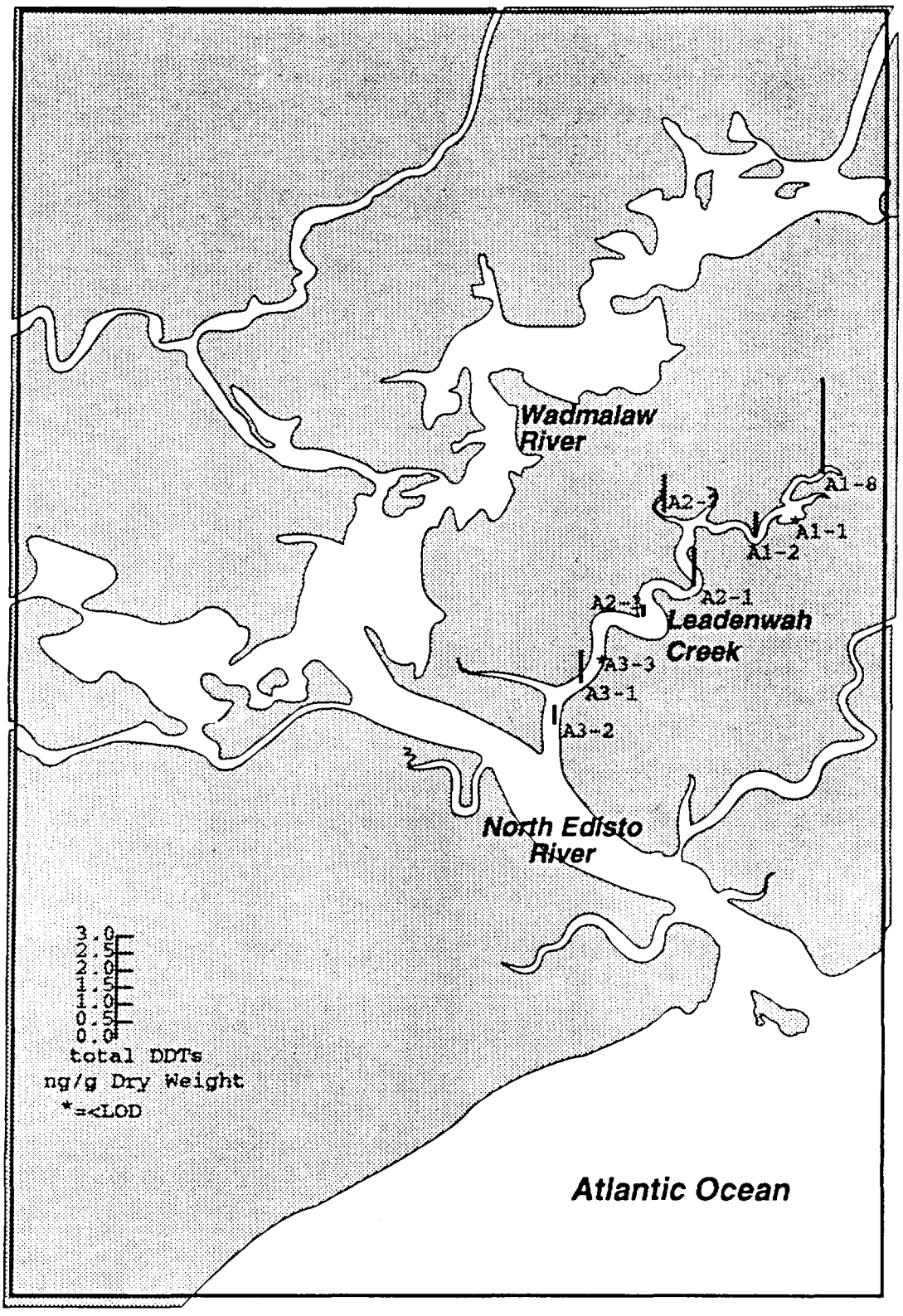


Figure 36. Concentrations of total DDTs in sediments from Leadenwah Creek.

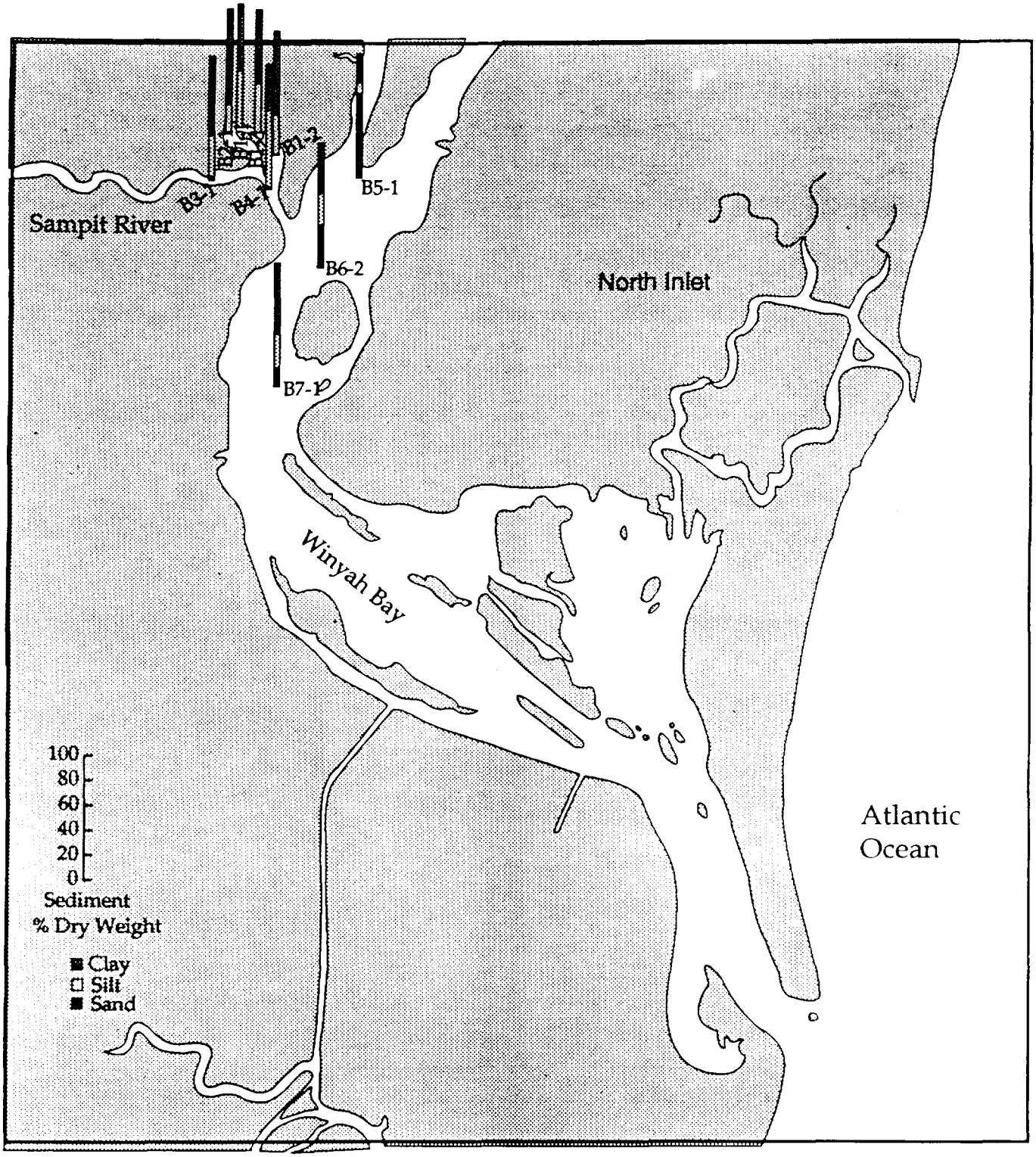


Figure 37. Concentrations of sand, silt and clay in sediments from Winyah Bay.

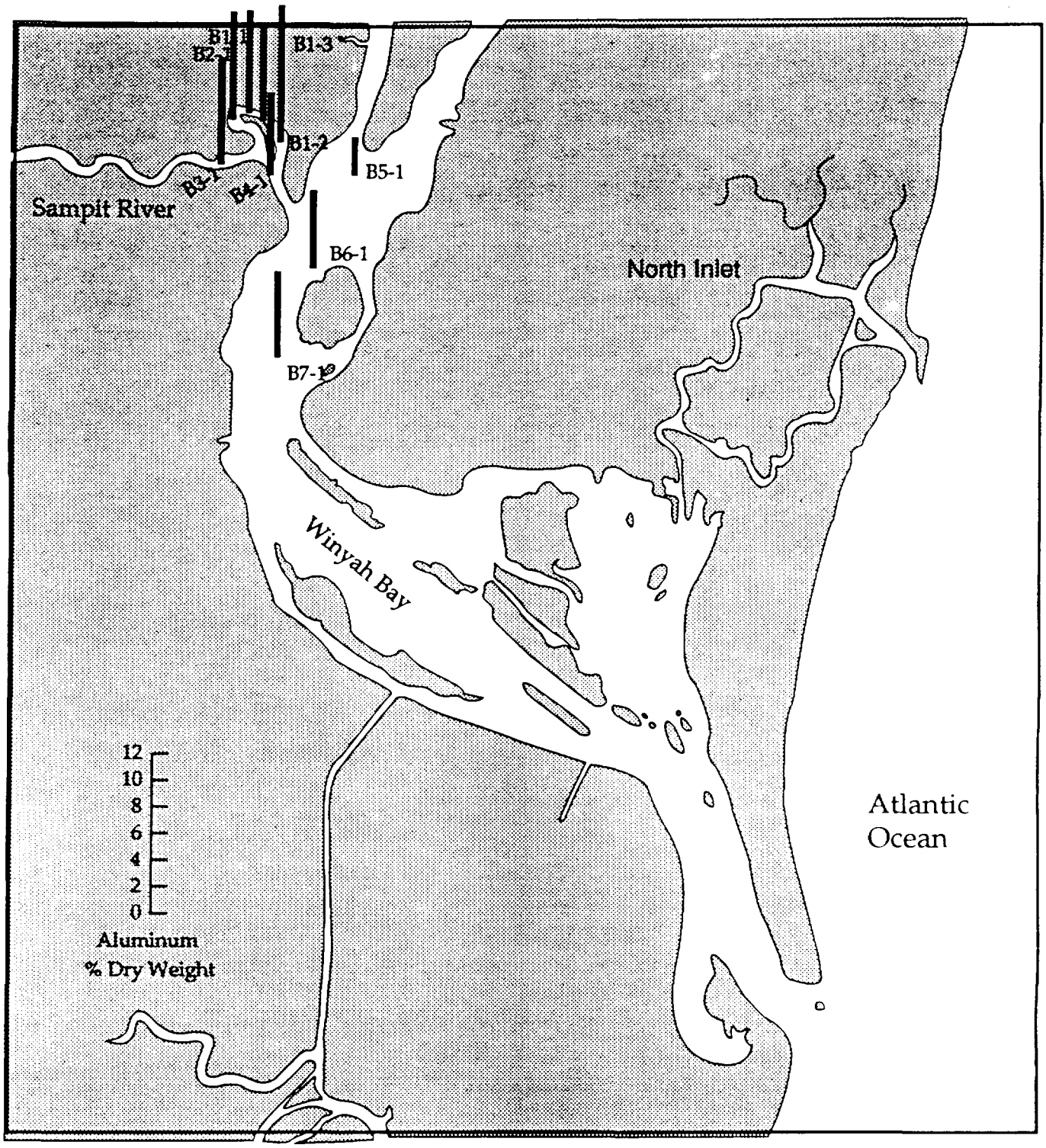


Figure 38. Concentrations of aluminum in sediments from Winyah Bay.

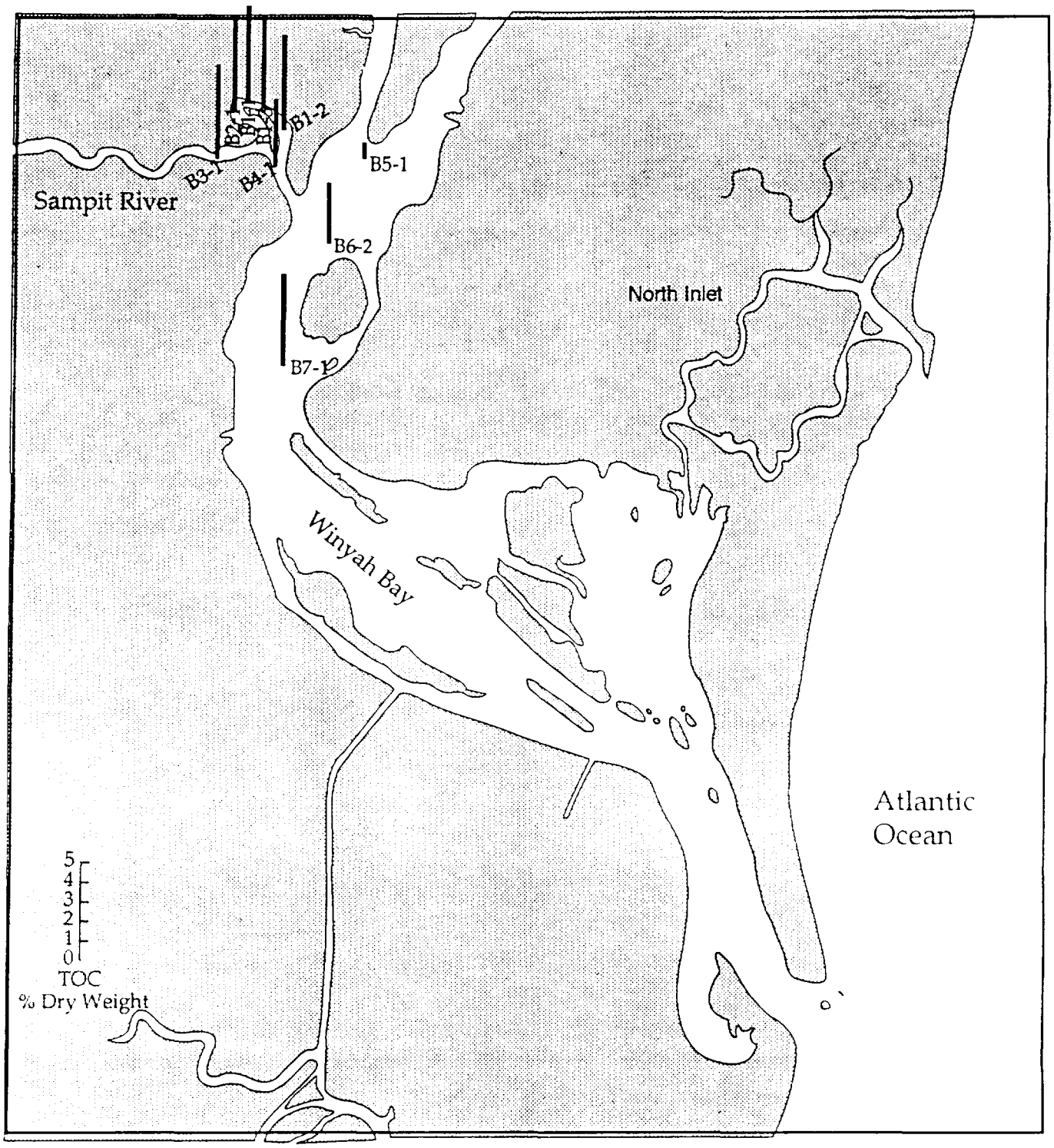


Figure 39. Concentrations of total organic carbon in sediments from Winyah Bay.

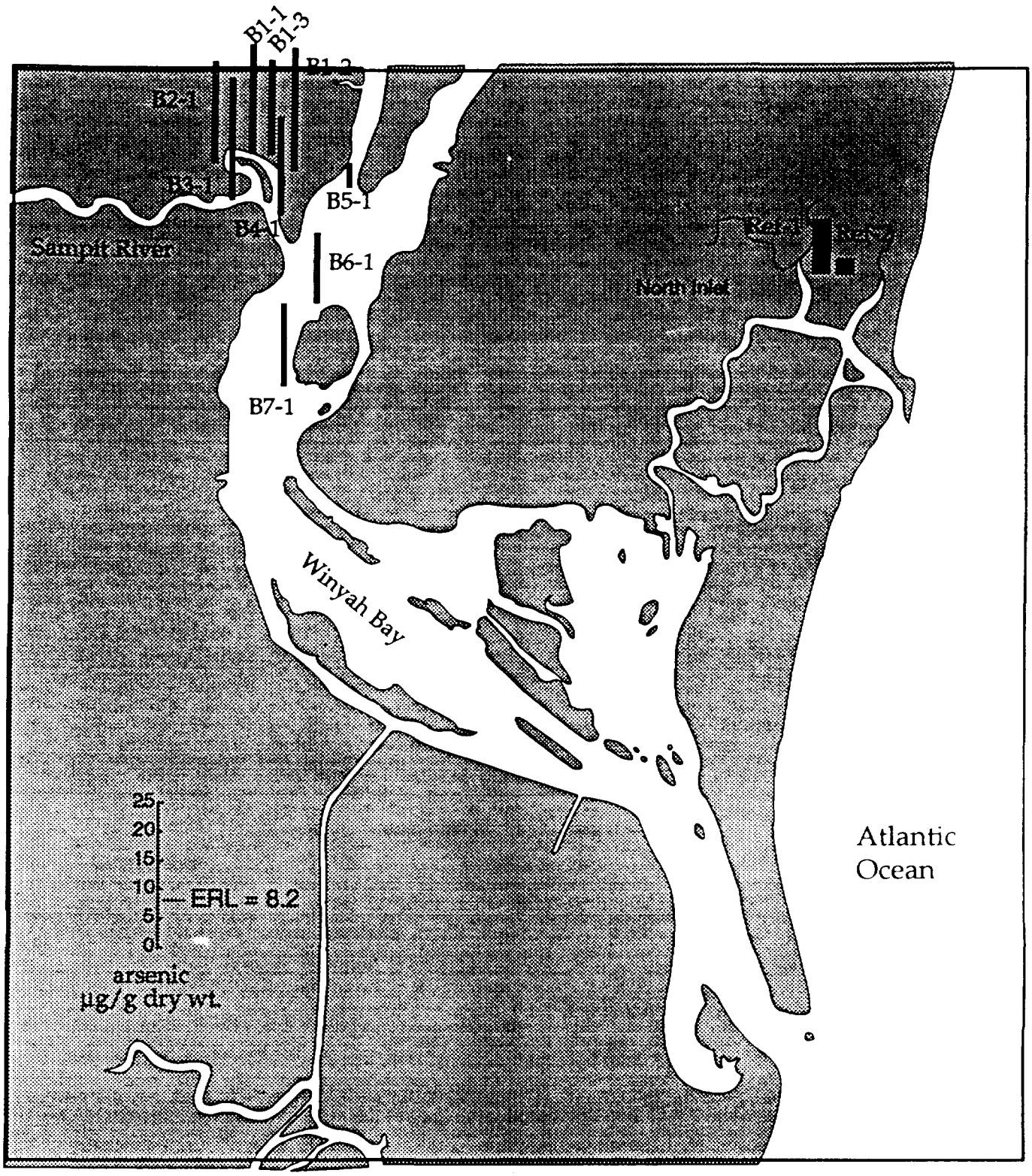


Figure 40. Concentrations of arsenic in sediments from Winyah Bay.

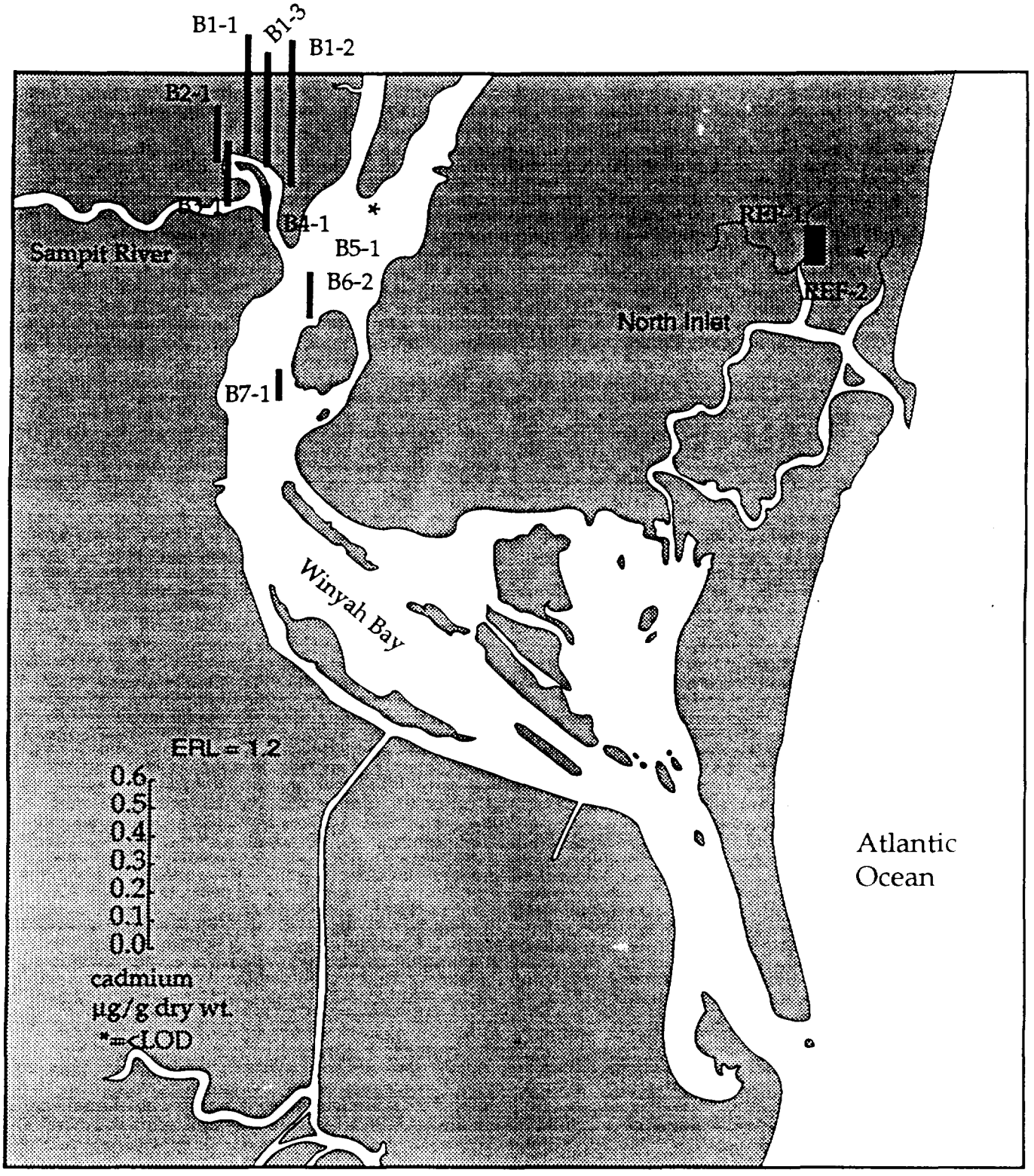


Figure 41. Concentrations of cadmium in sediments from Winyah Bay.

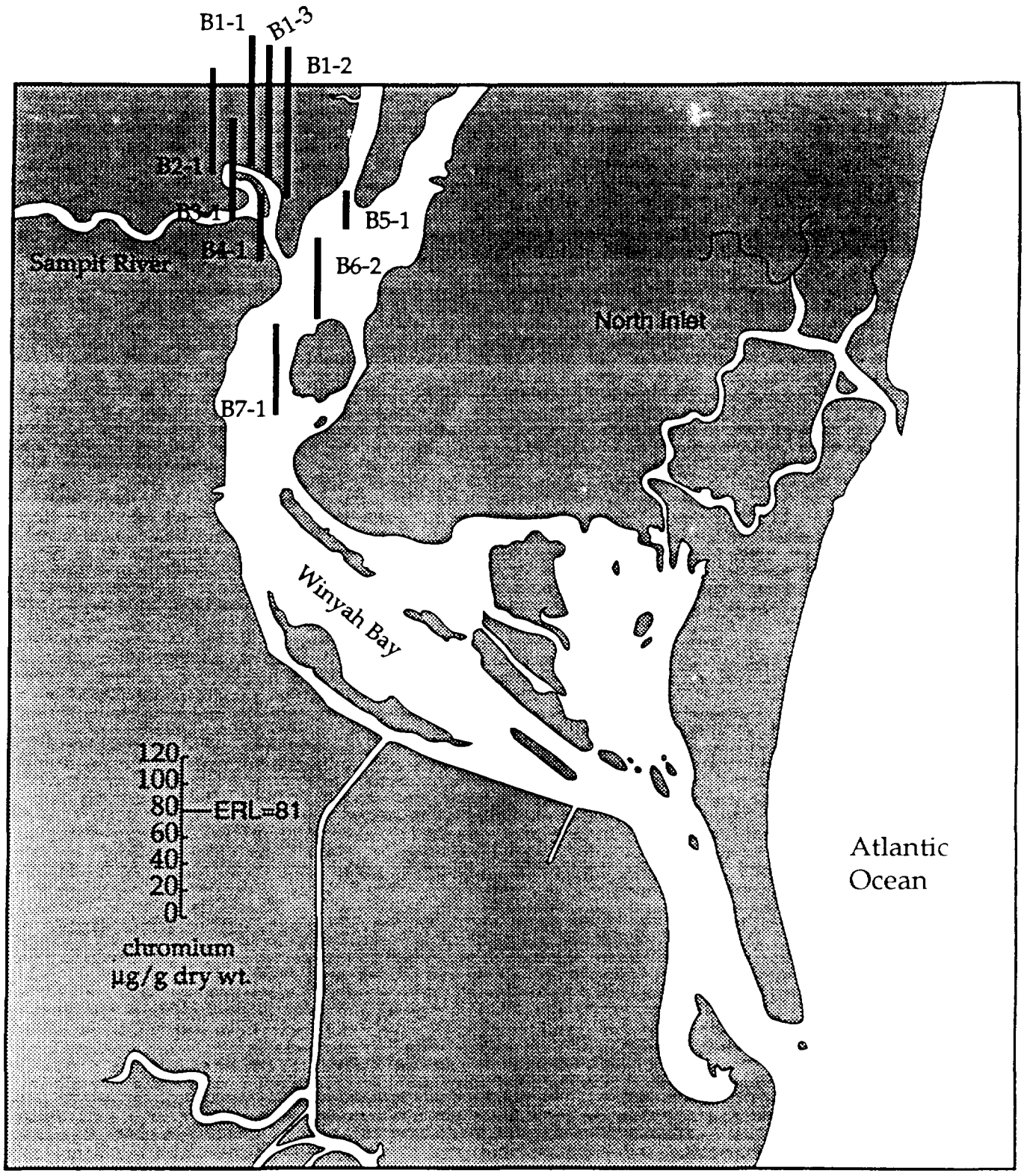


Figure 42. Concentrations of chromium in sediments from Winyah Bay.

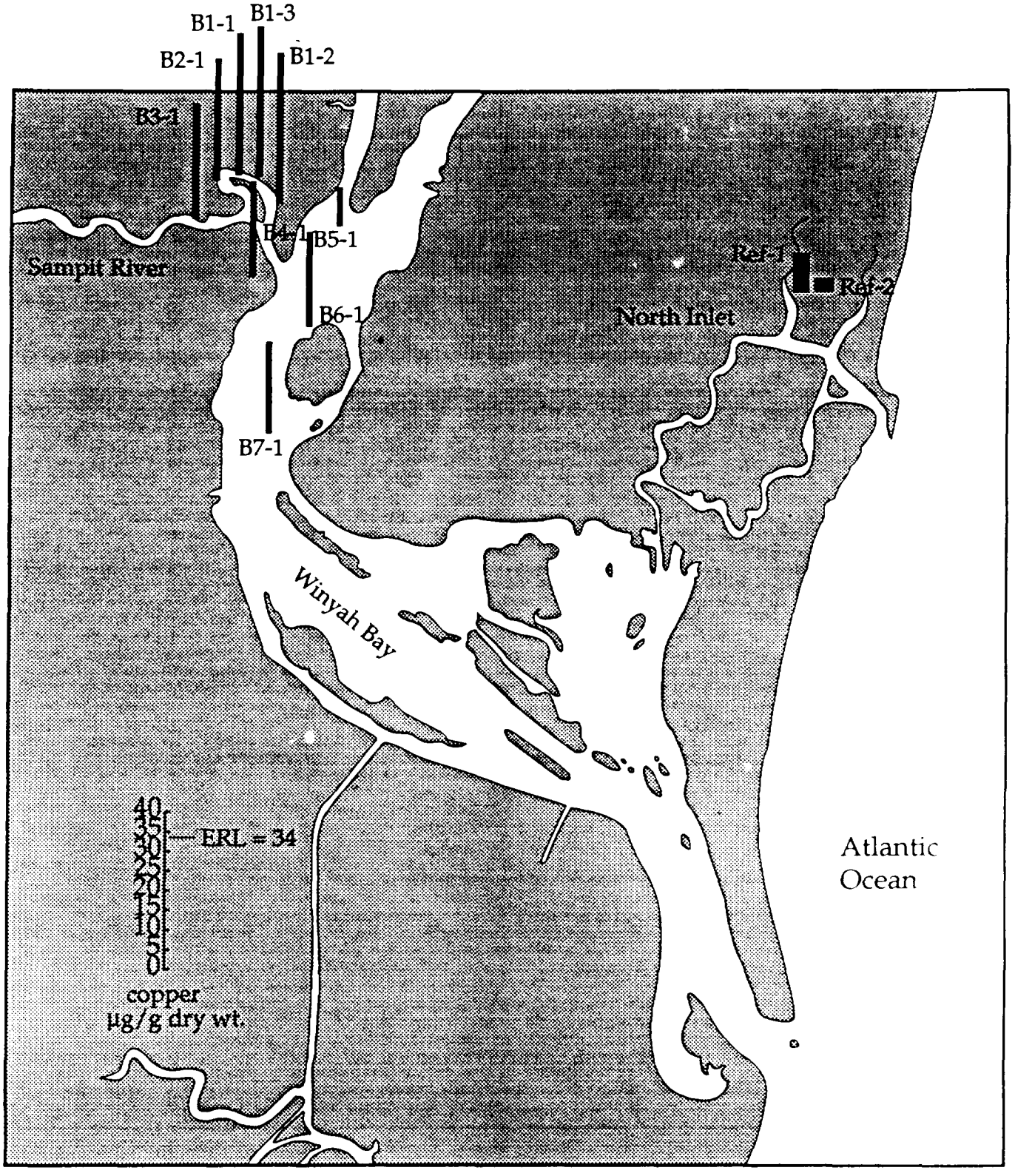


Figure 43. Concentrations of copper in sediments from Winyah Bay.

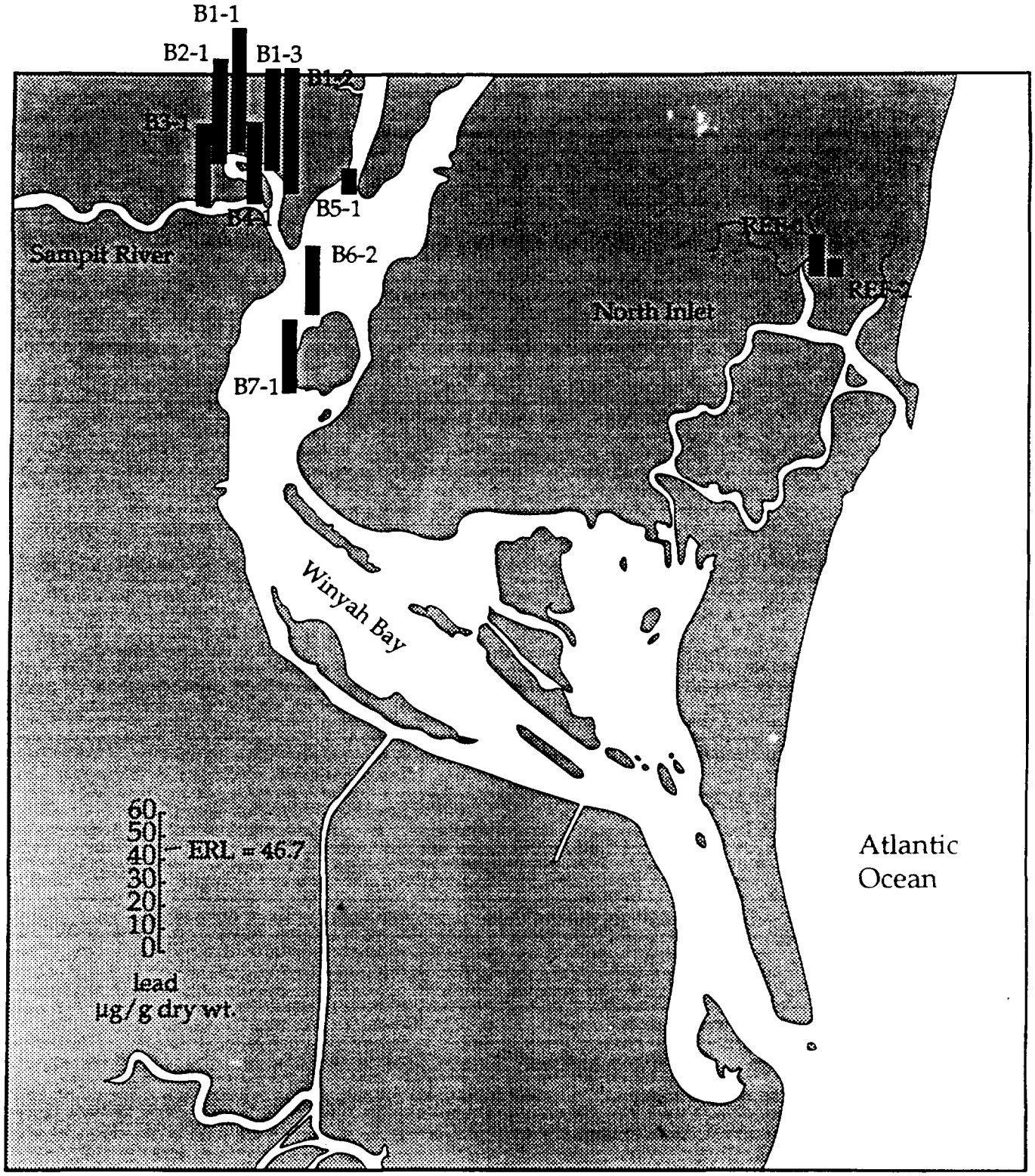


Figure 44. Concentrations of lead in sediments from Winyah Bay.

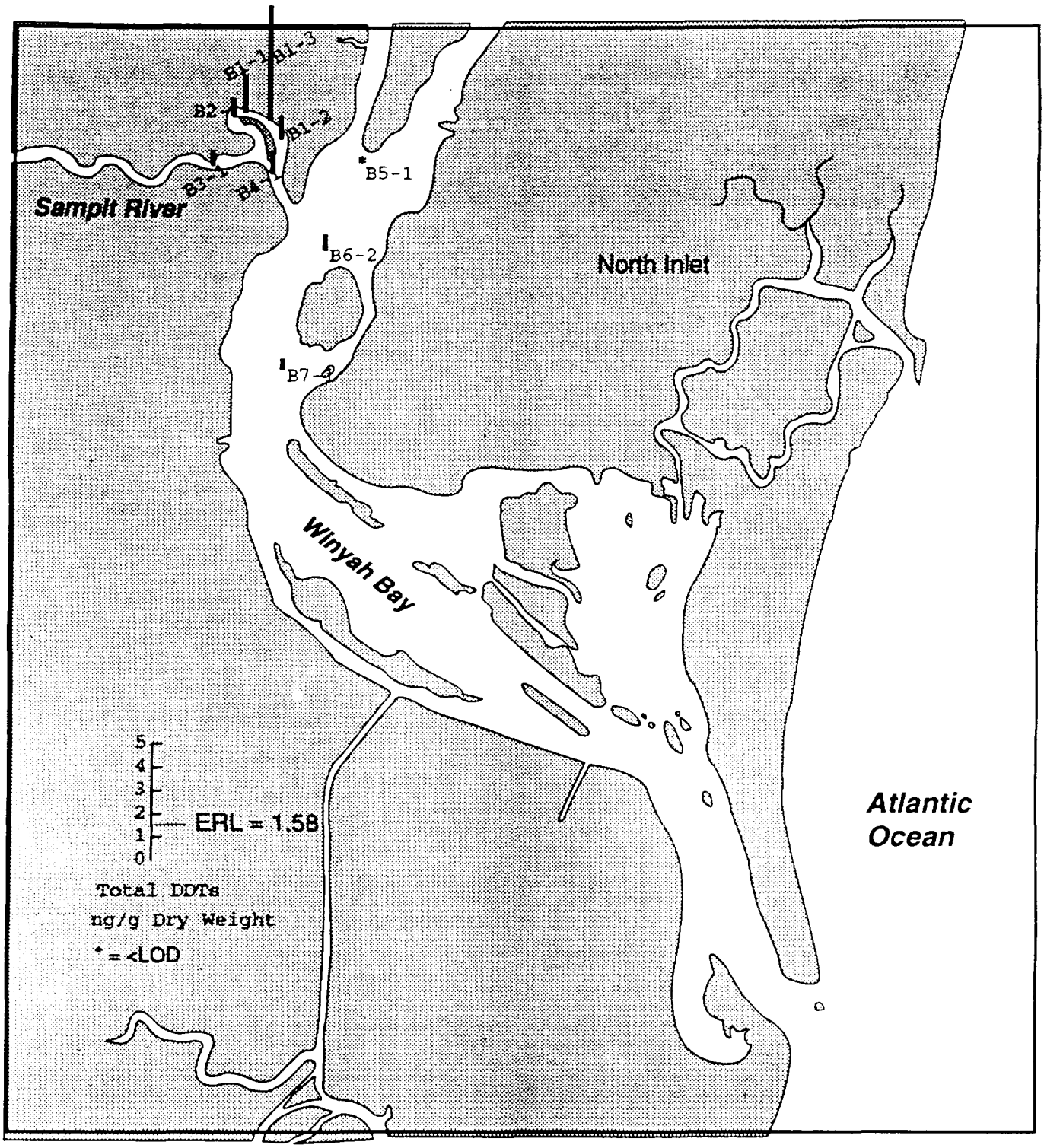


Figure 45. Concentrations of total DDTs in sediments from Winyah Bay.

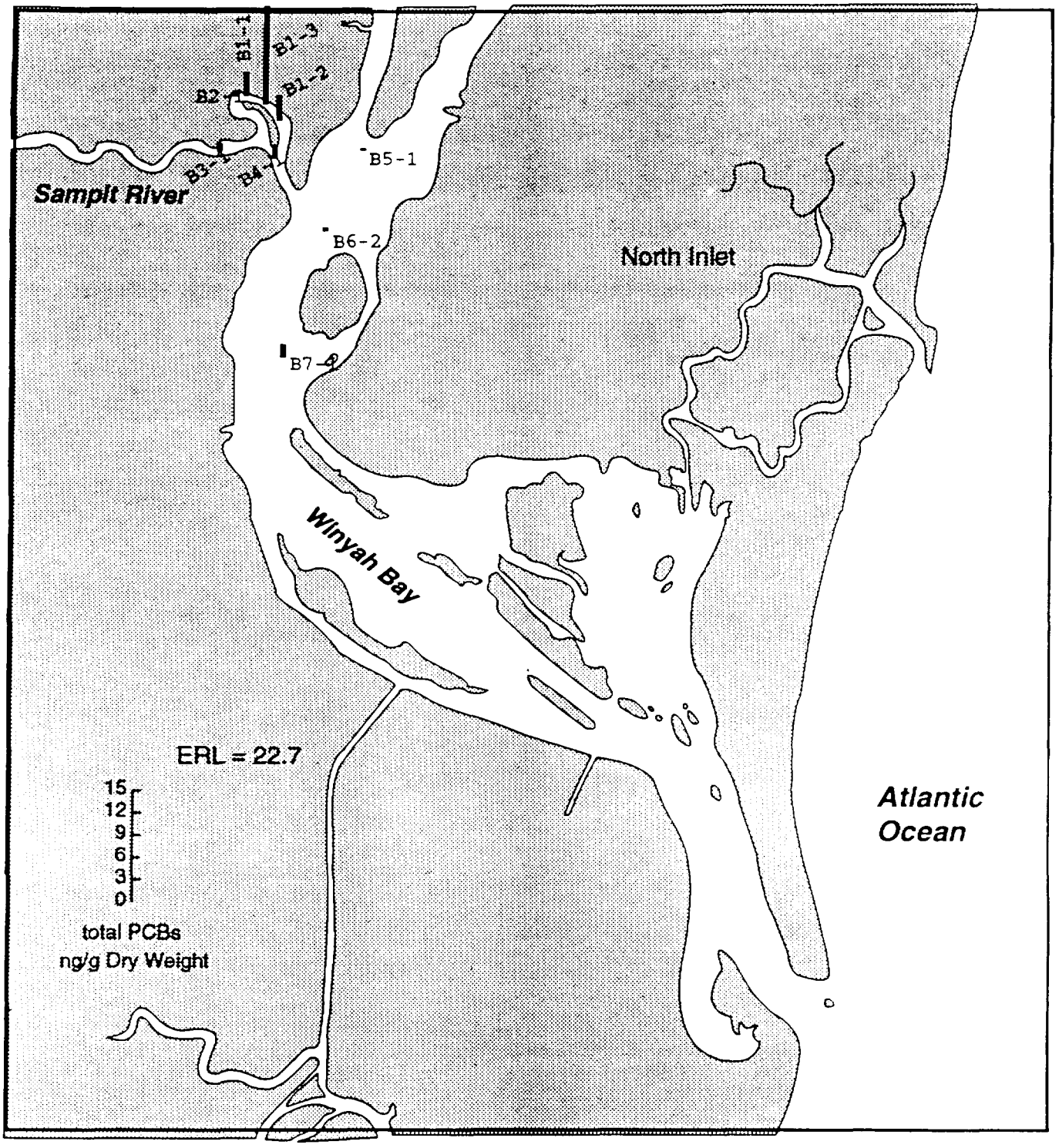


Figure 46. Concentrations of total PCBs in sediments from Winyah Bay.

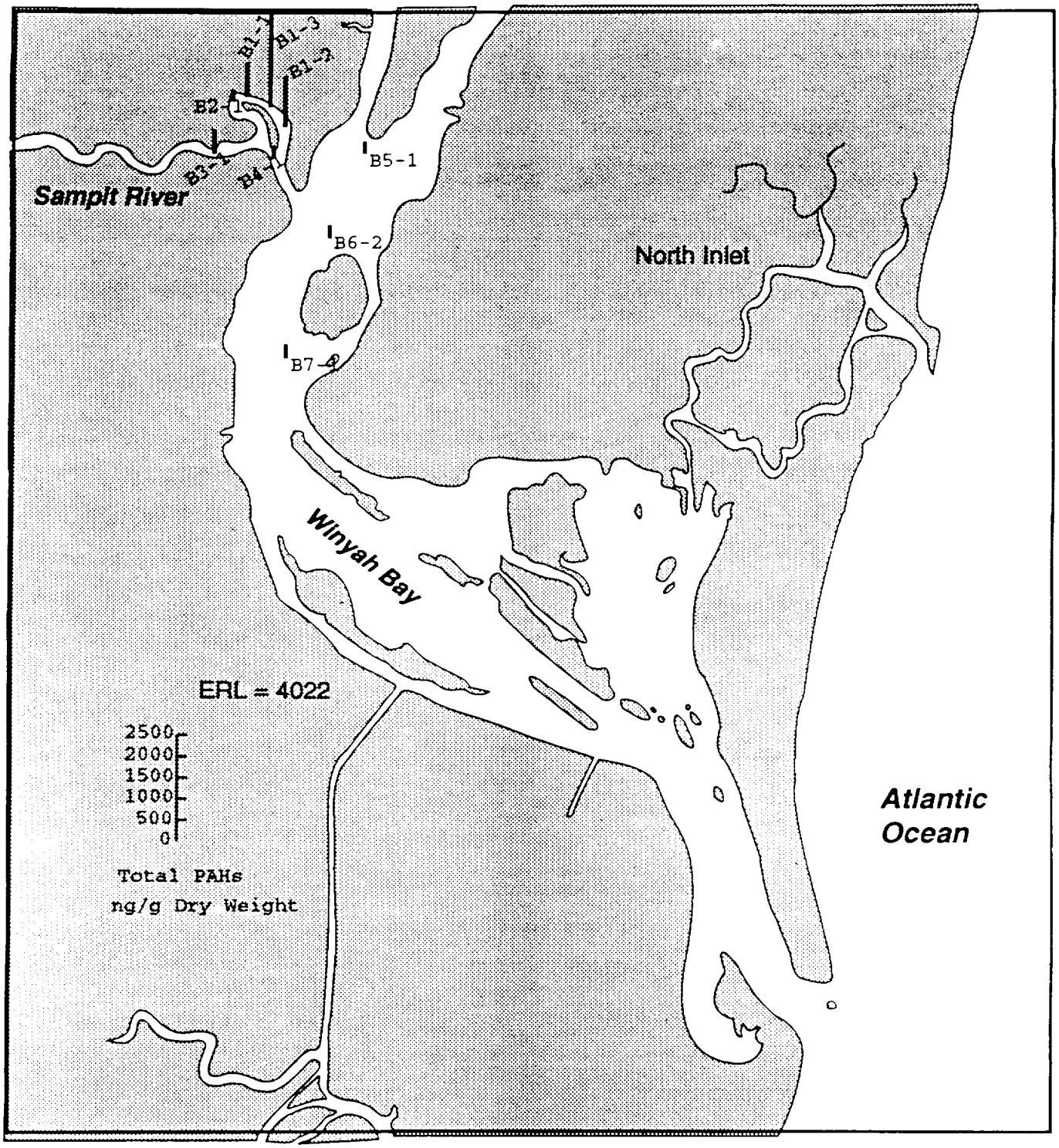


Figure 47. Concentrations of total PAHs in sediments from Winyah Bay.

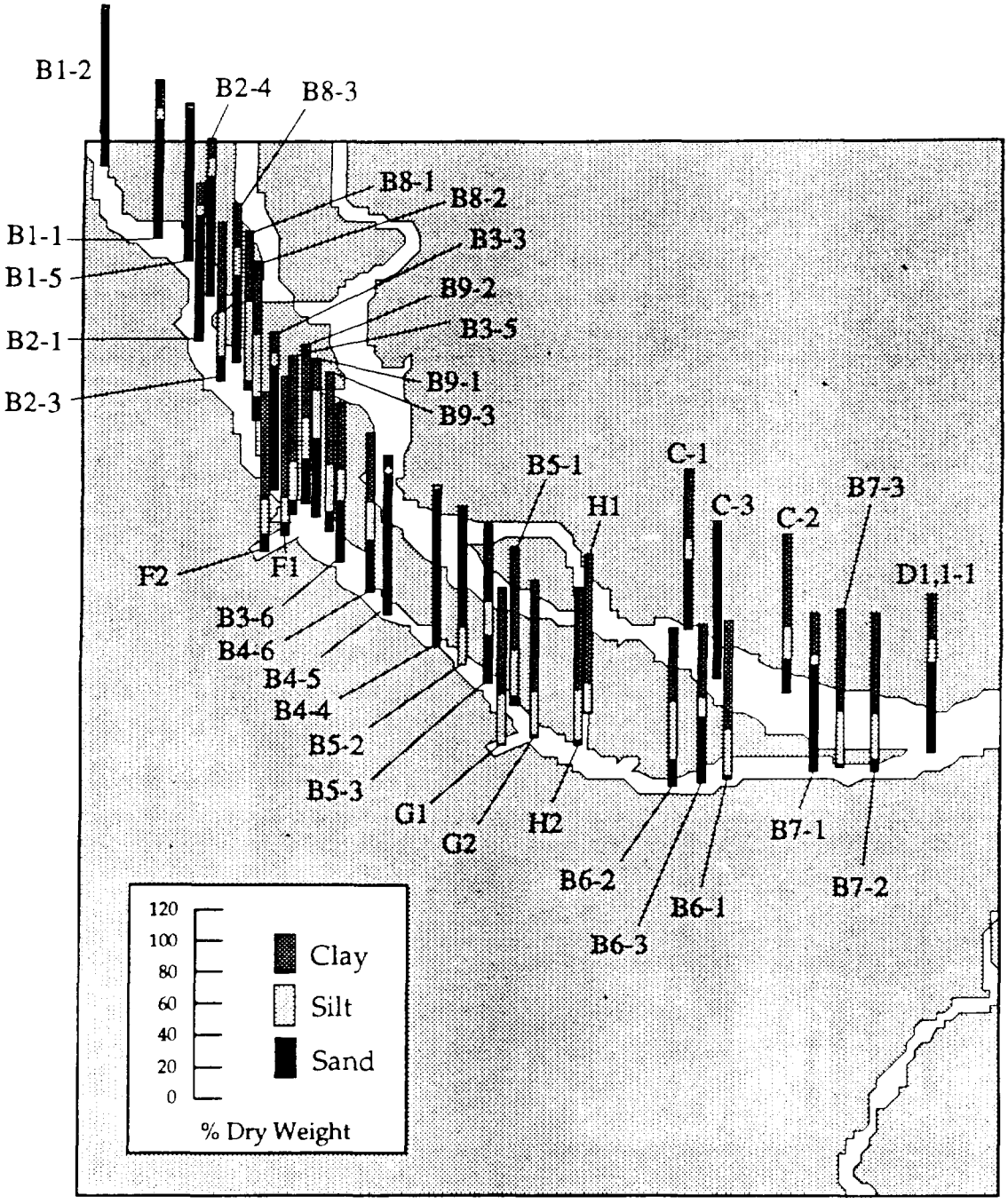


Figure 48. Concentrations of sand, silt, and clay in sediments from the upper Savannah River channel.

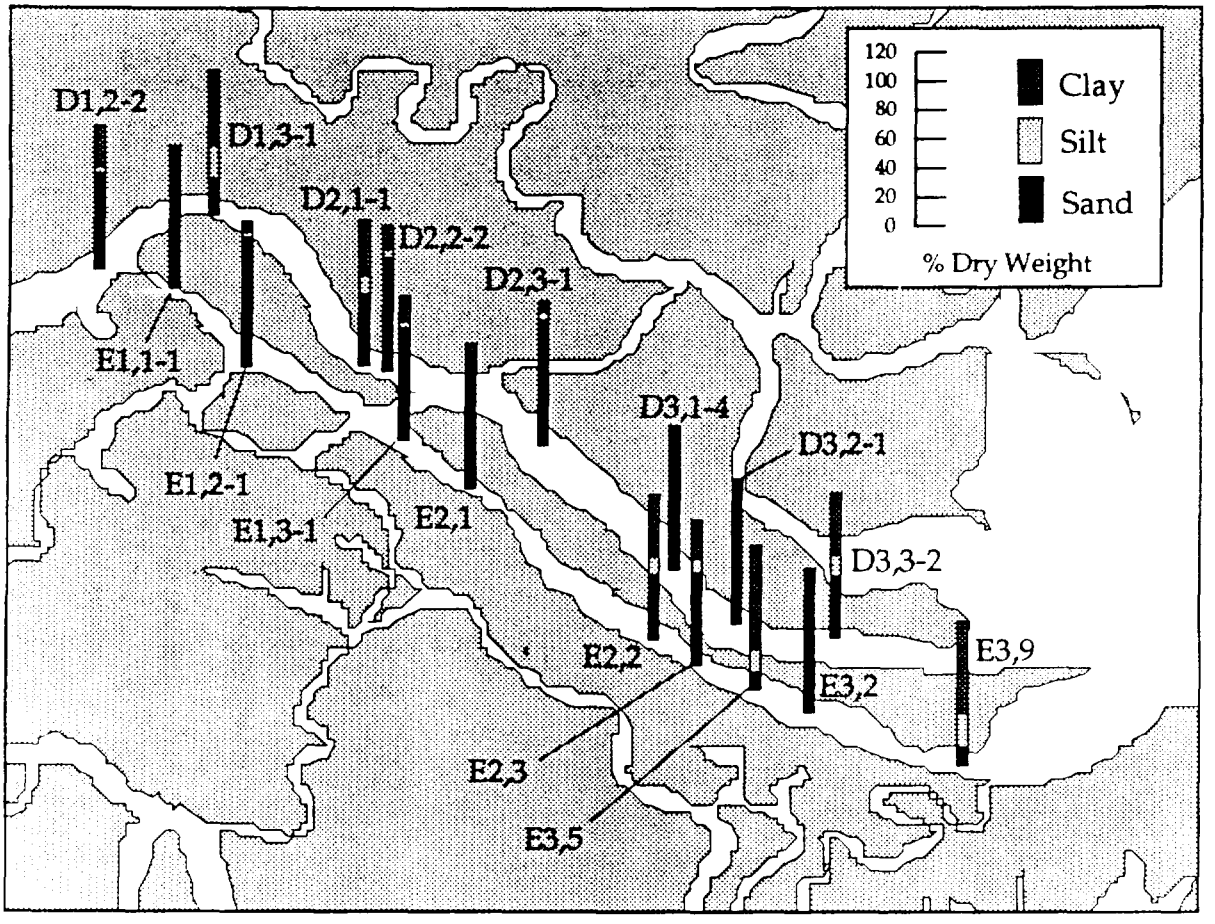


Figure 49. Concentrations of sand, silt, and clay in sediments from the lower Savannah River channel.

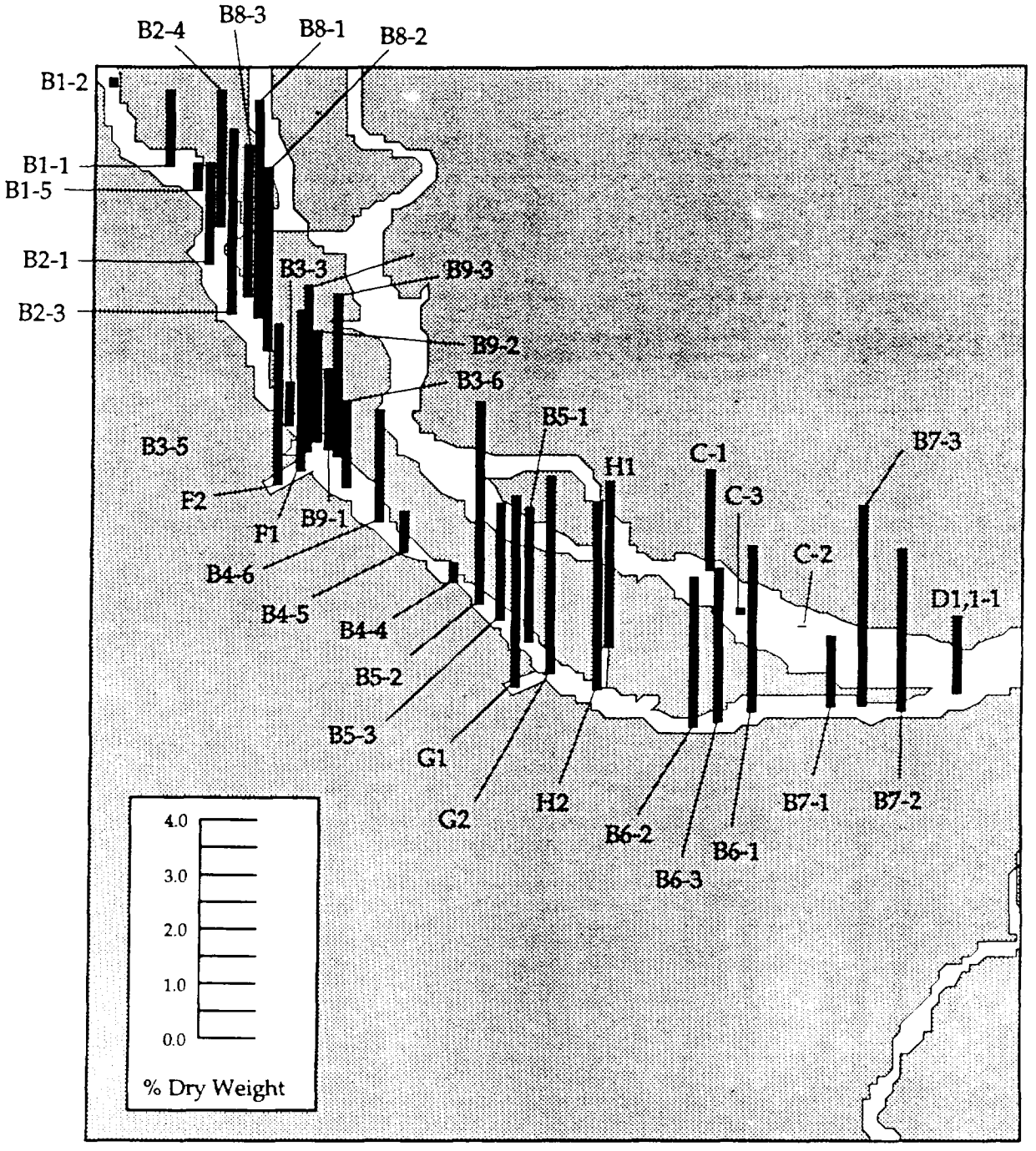


Figure 50. Concentrations of total organic carbon in sediments from the upper Savannah River channel.

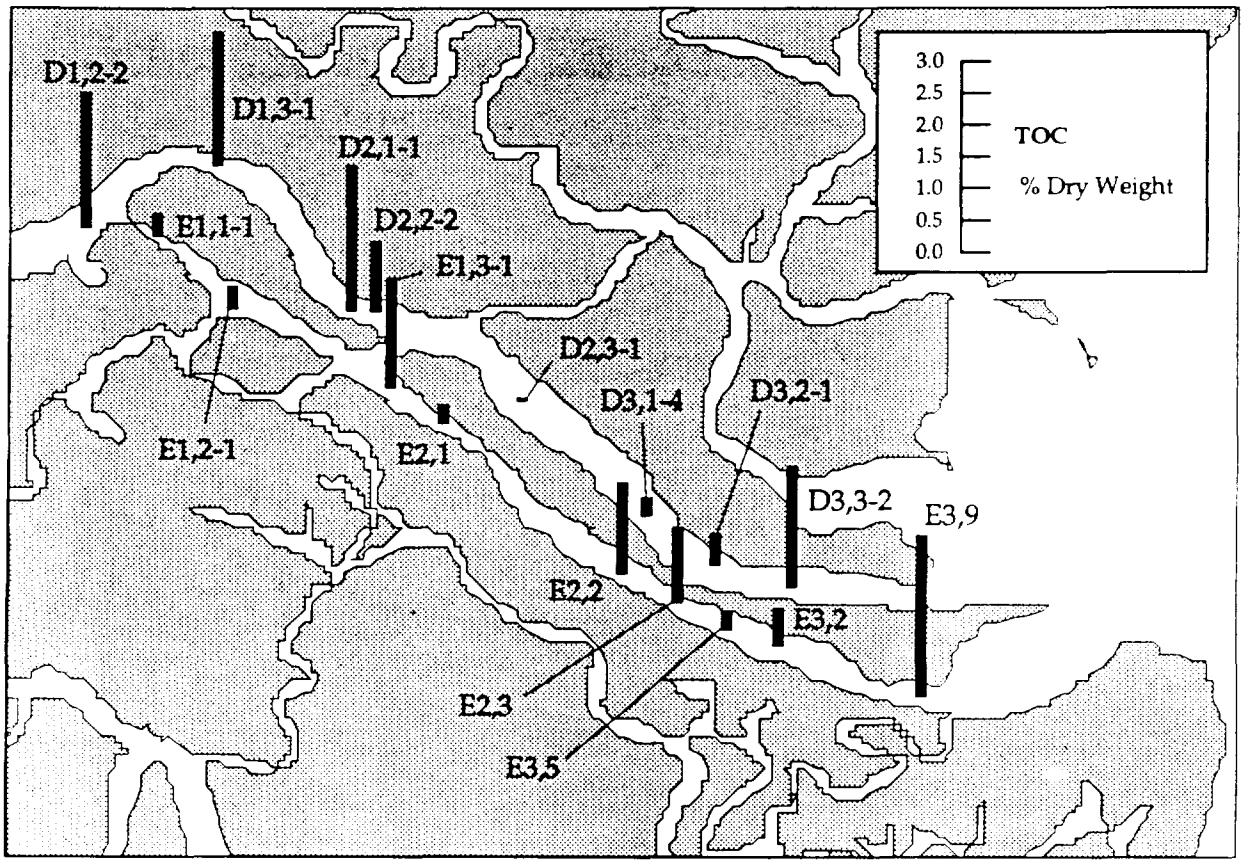


Figure 51. Concentrations of total organic carbon in sediments from the lower Savannah River channel.

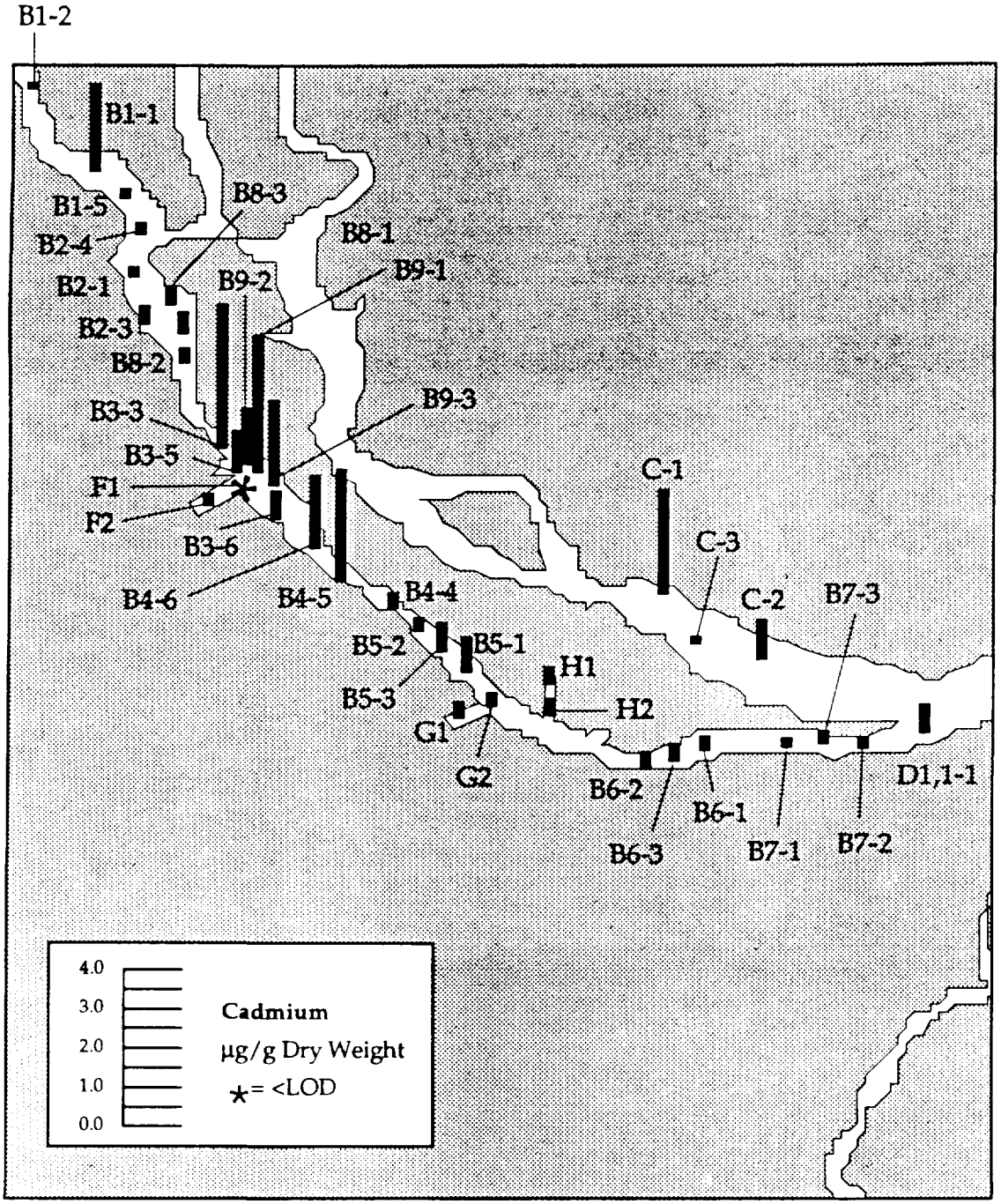


Figure 52. Concentrations of cadmium in sediments from the upper Savannah River channel.

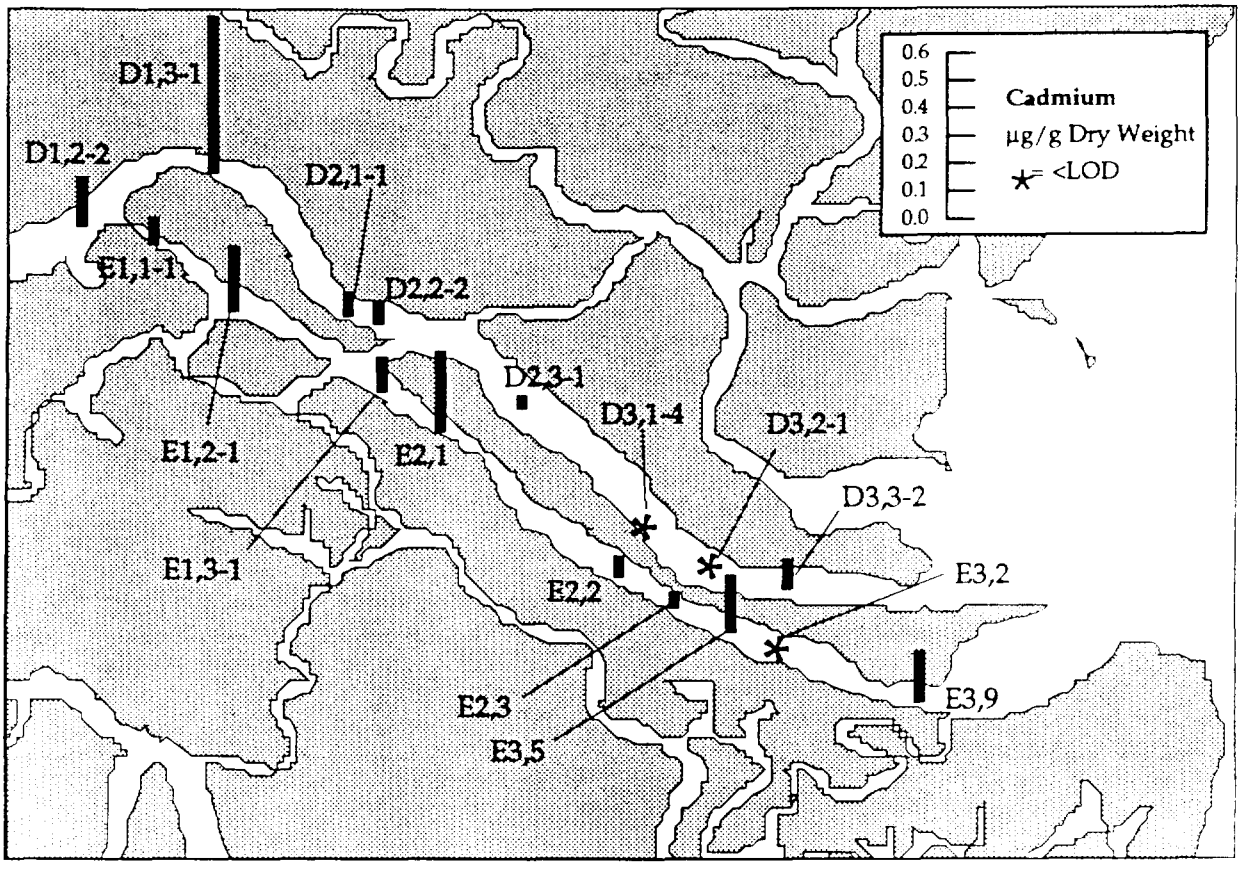


Figure 53. Concentrations of cadmium in sediments from the lower Savannah River channel.

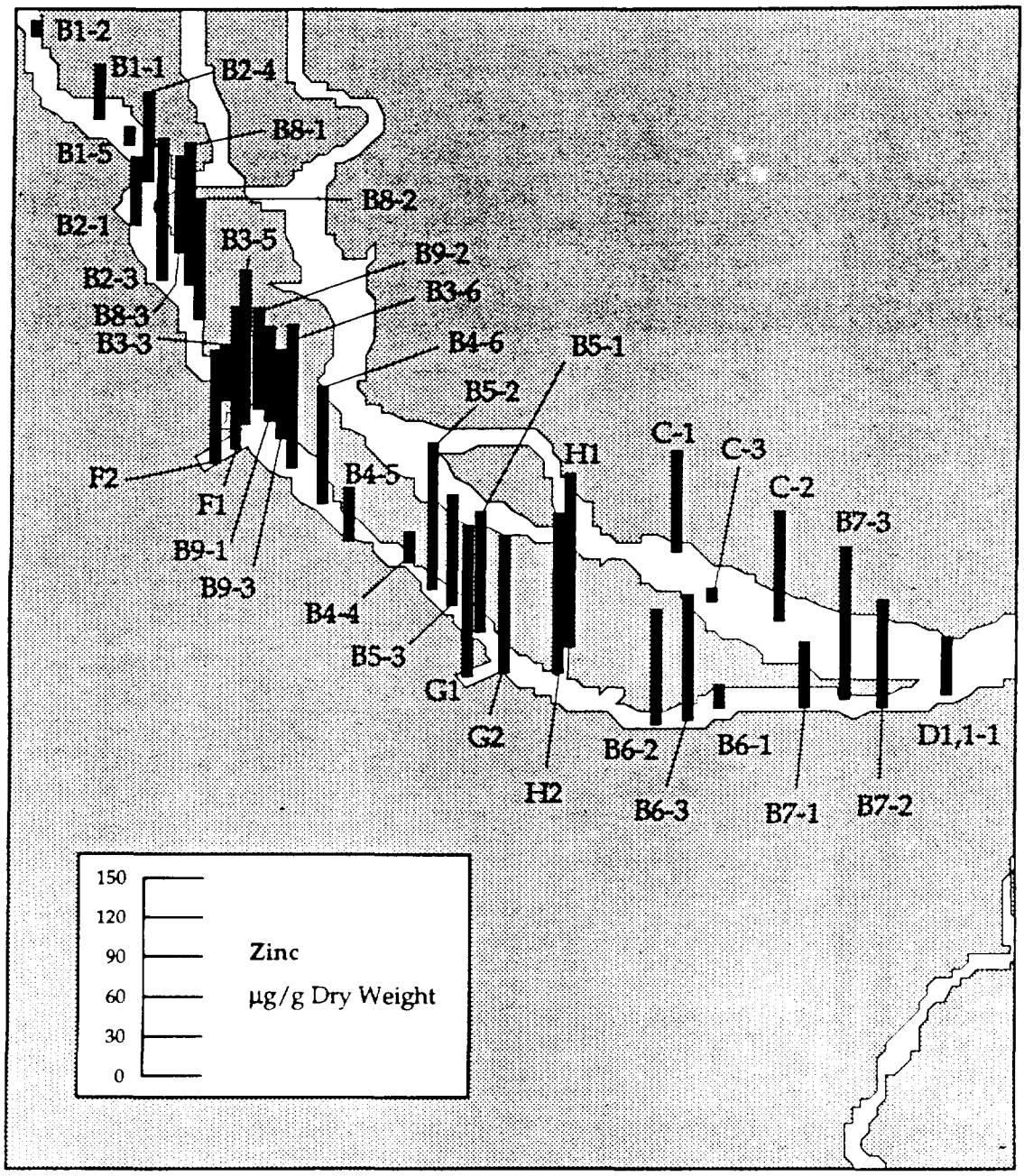


Figure 54. Concentrations of zinc in sediments from the upper Savannah River channel.

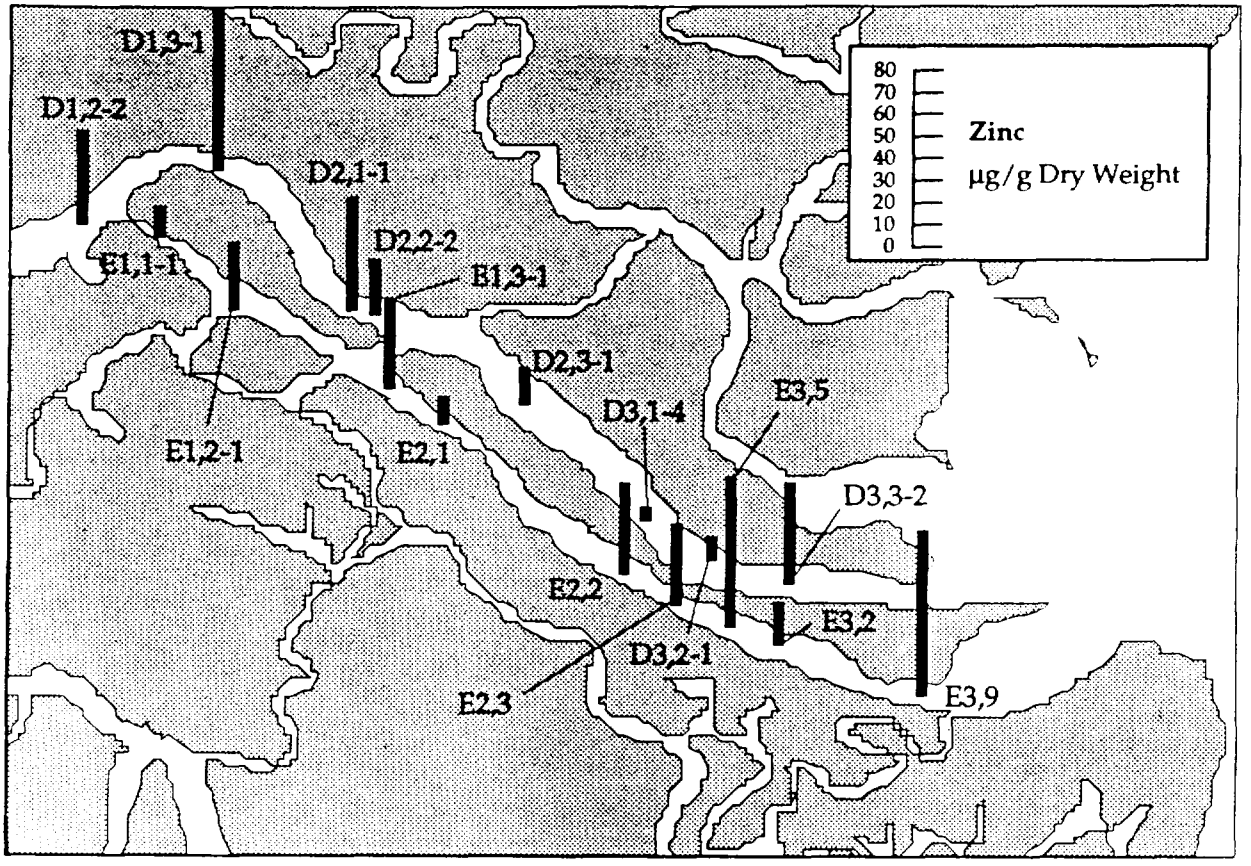


Figure 55. Concentrations of zinc sediments from the lower Savannah River channel.

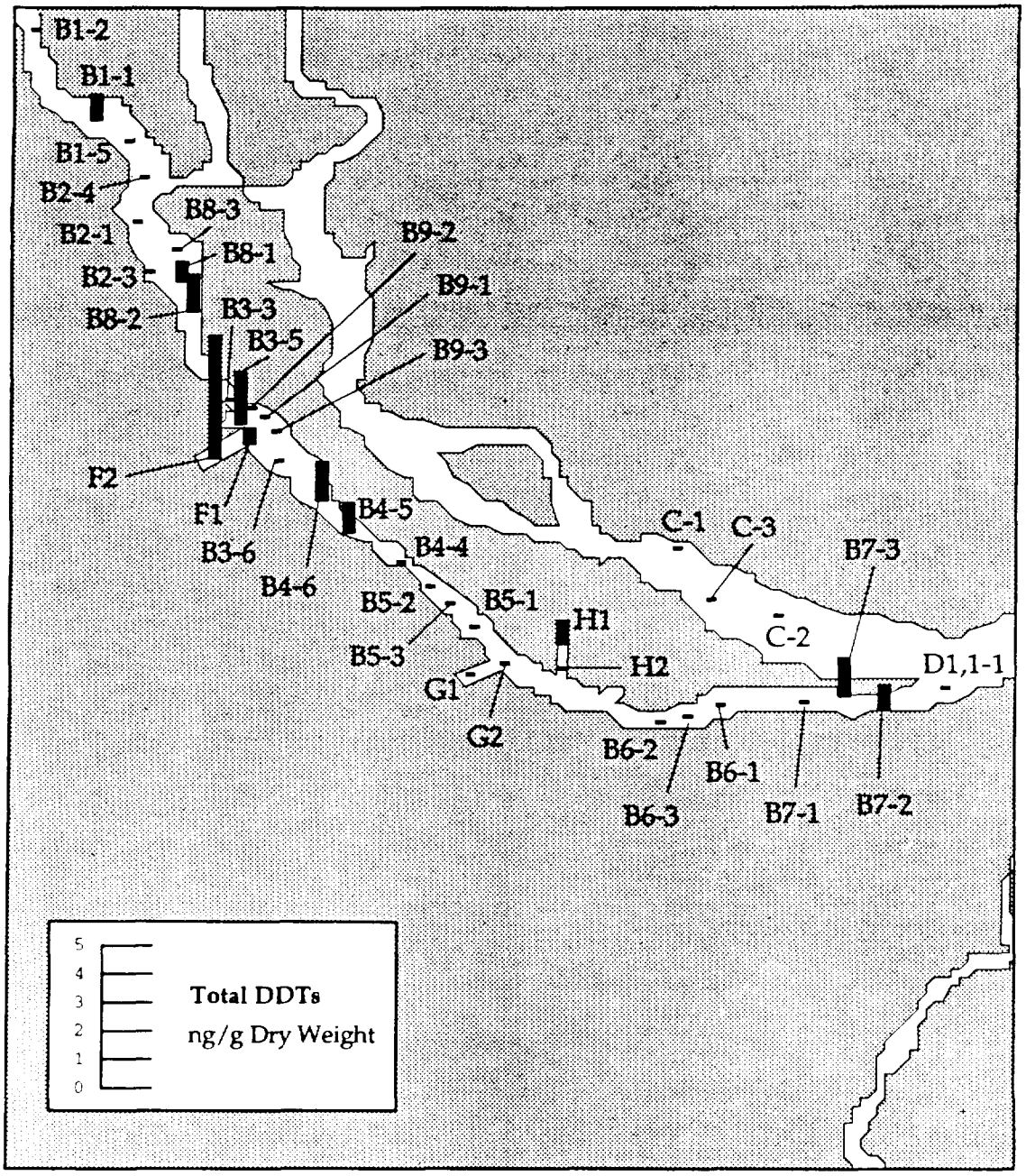


Figure 56. Concentrations of total DDTs in sediments from the upper Savannah River channel.

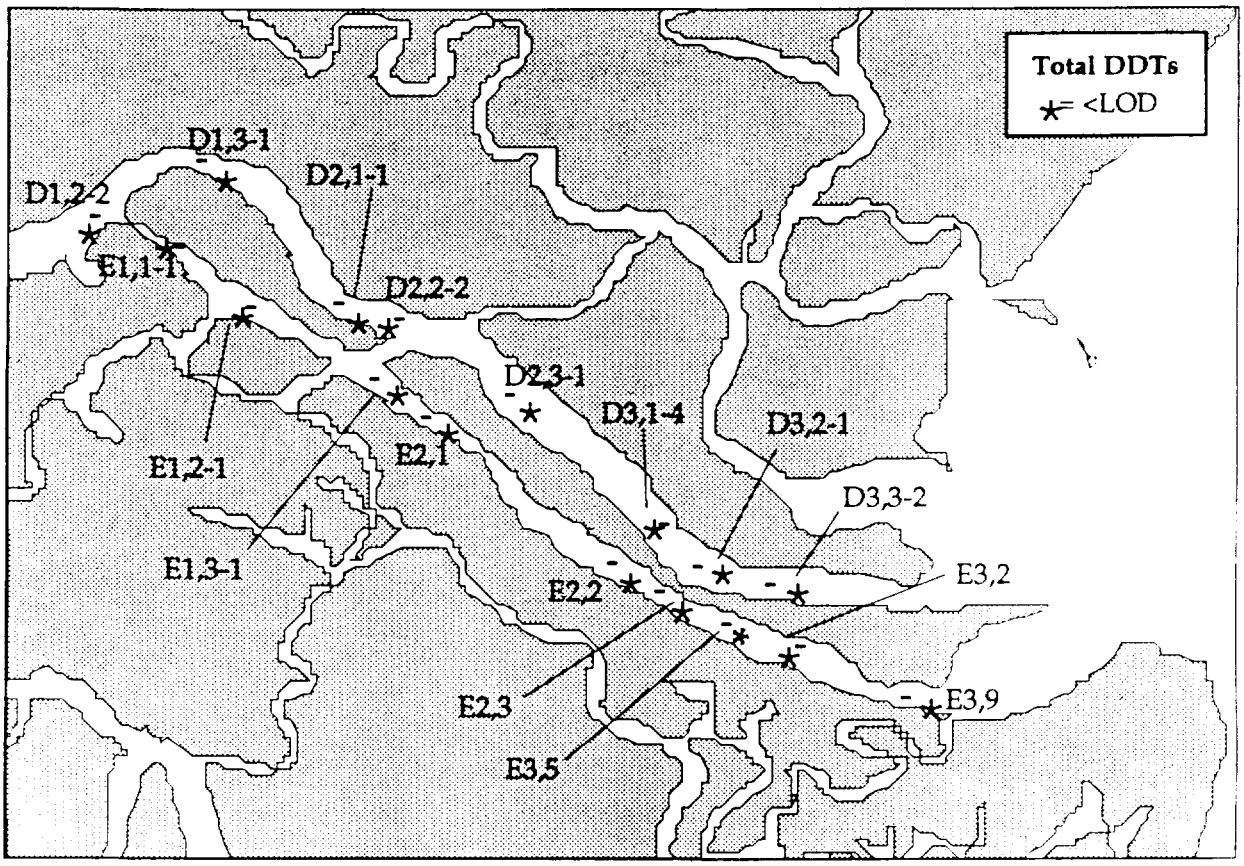


Figure 57. Concentrations of total DDTs in sediments from the lower Savannah River channel.

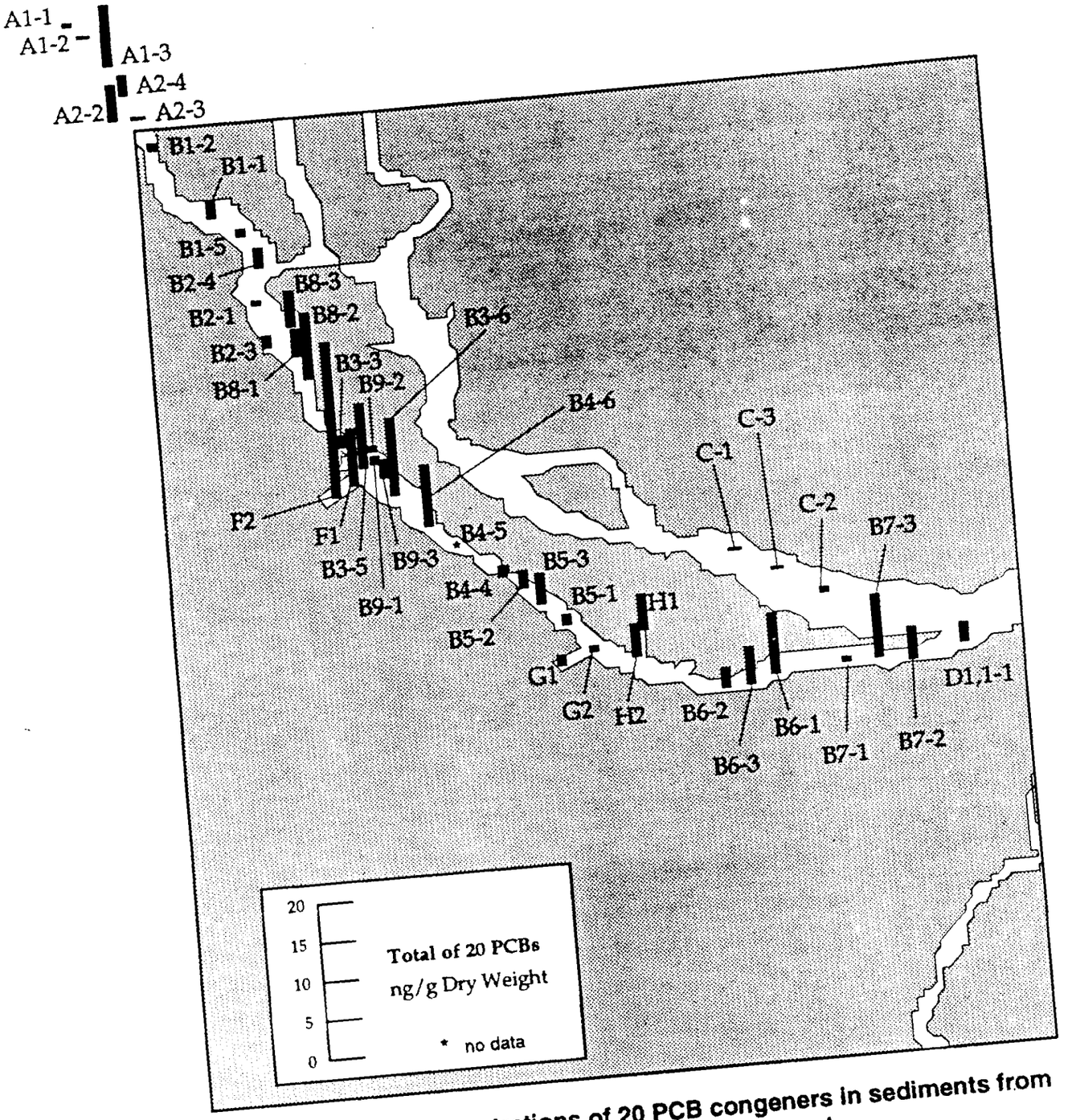


Figure 58. Total concentrations of 20 PCB congeners in sediments from the upper Savannah River channel.

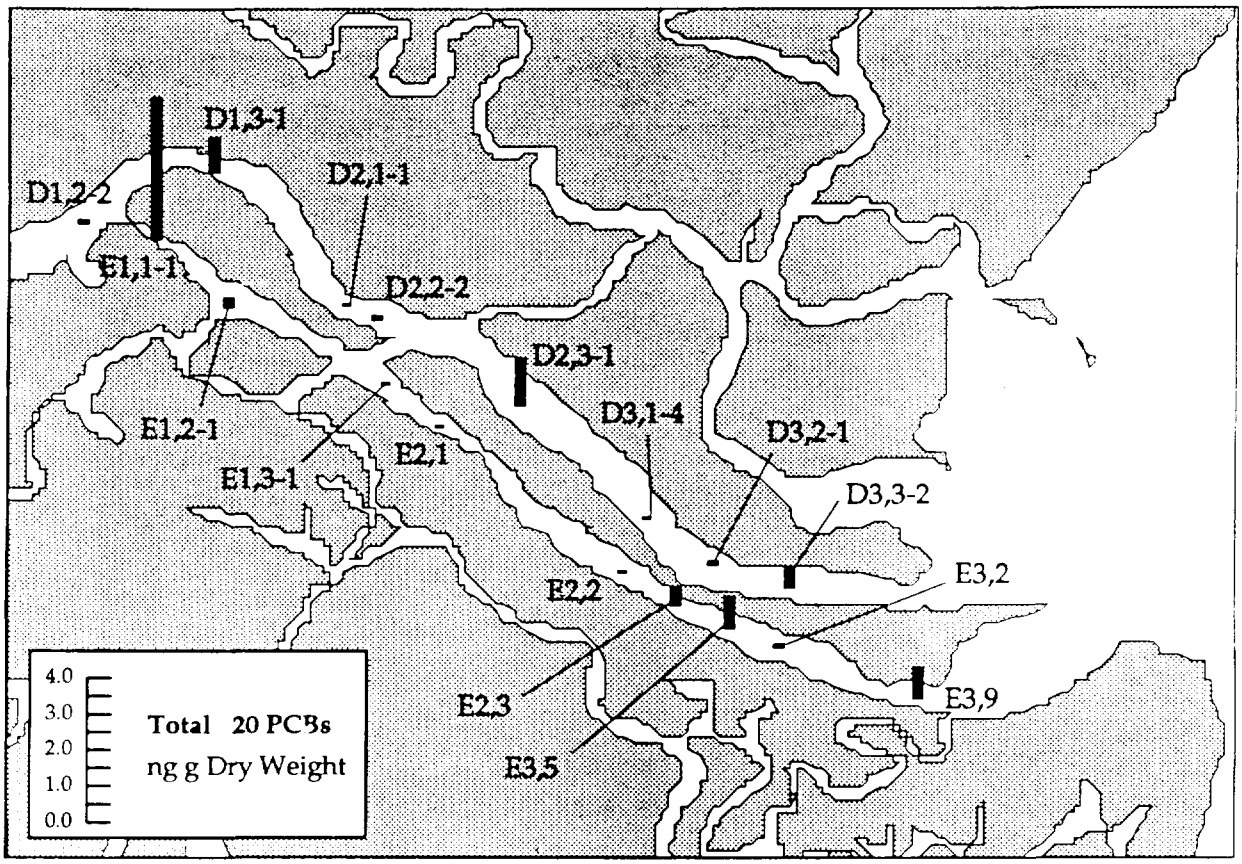


Figure 59. Total concentrations of total 20 PCB congeners in sediment from the lower Savannah River channel.

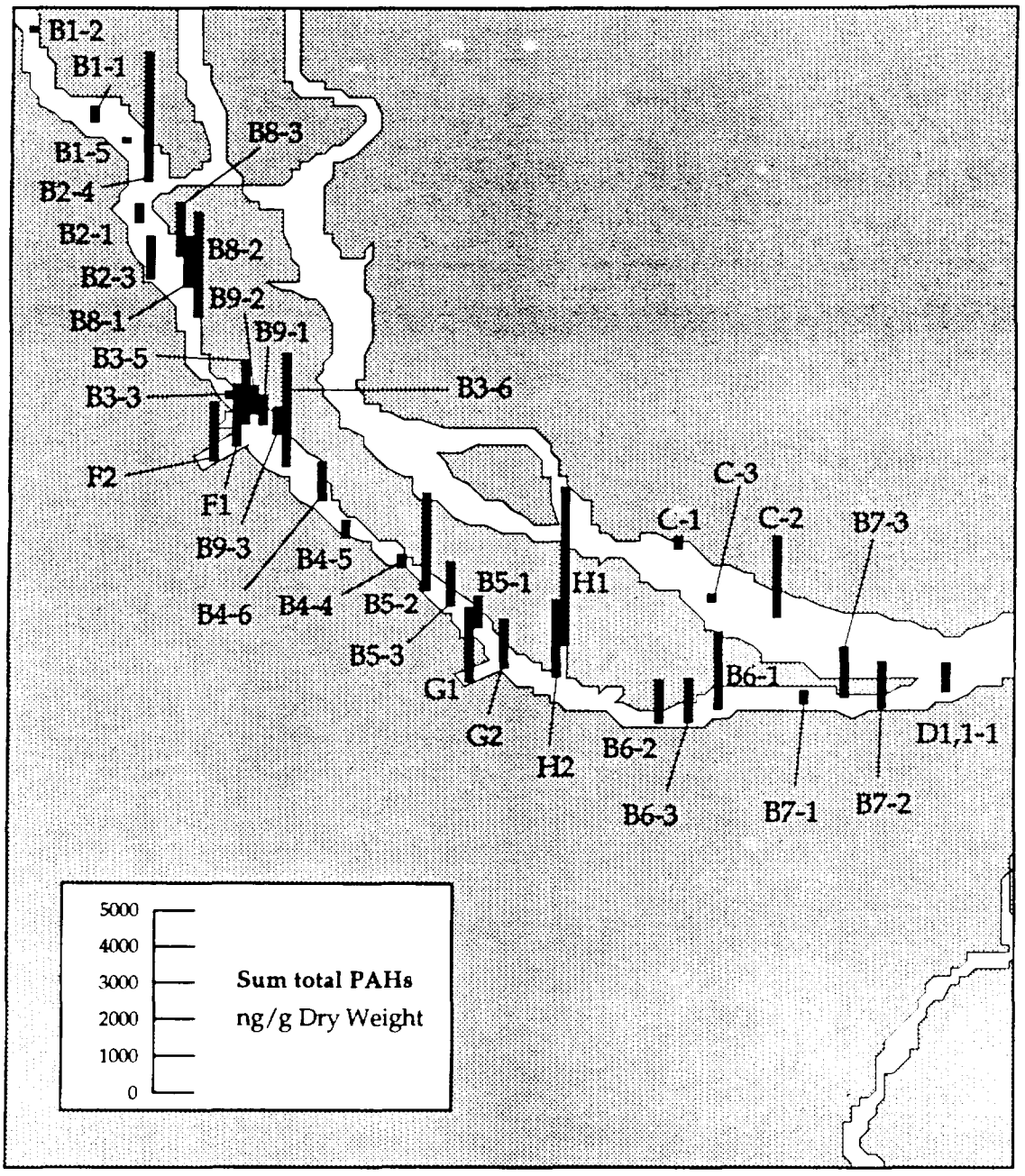


Figure 60. Concentrations of total PAH in sediments from the upper Savannah River channel.

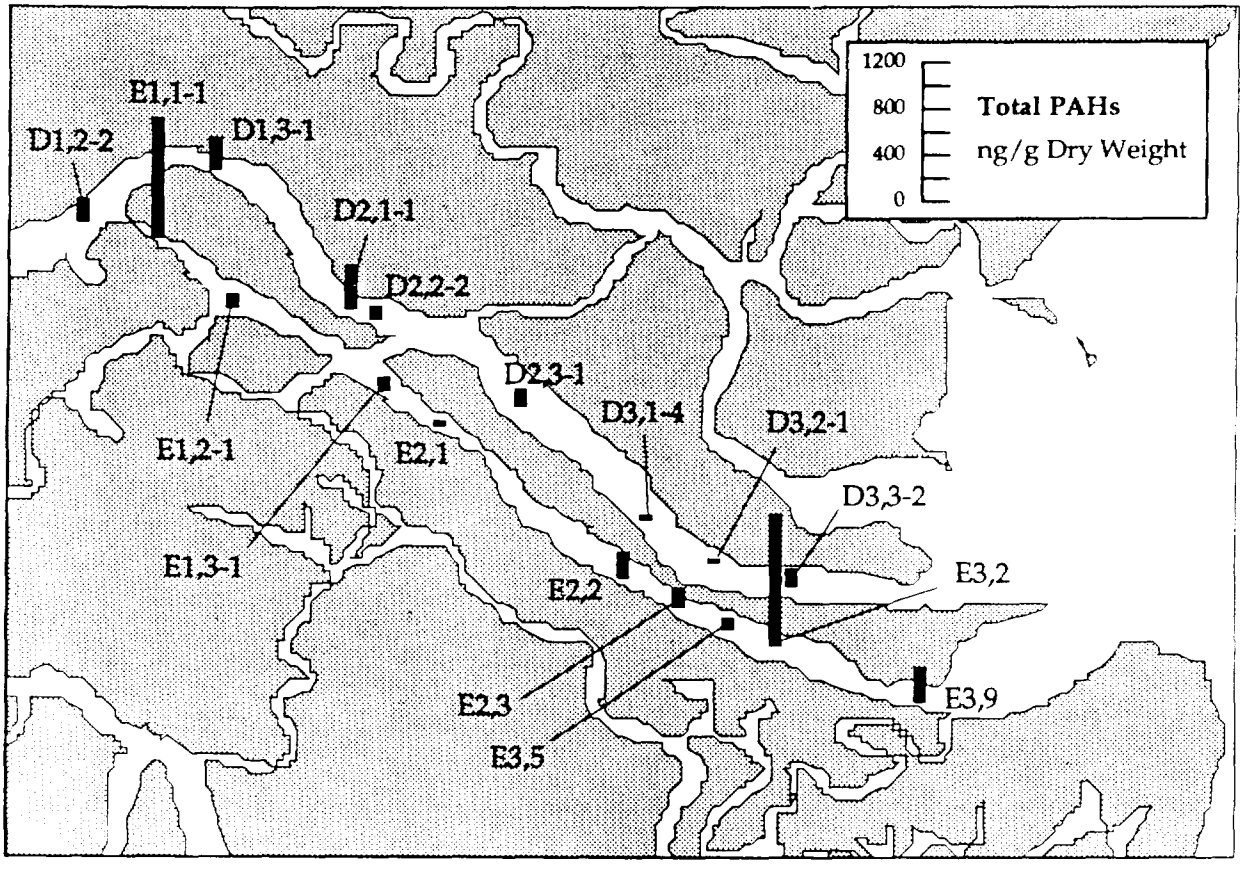


Figure 61. Concentrations of total PAHs in sediments from the lower Savannah River channel.

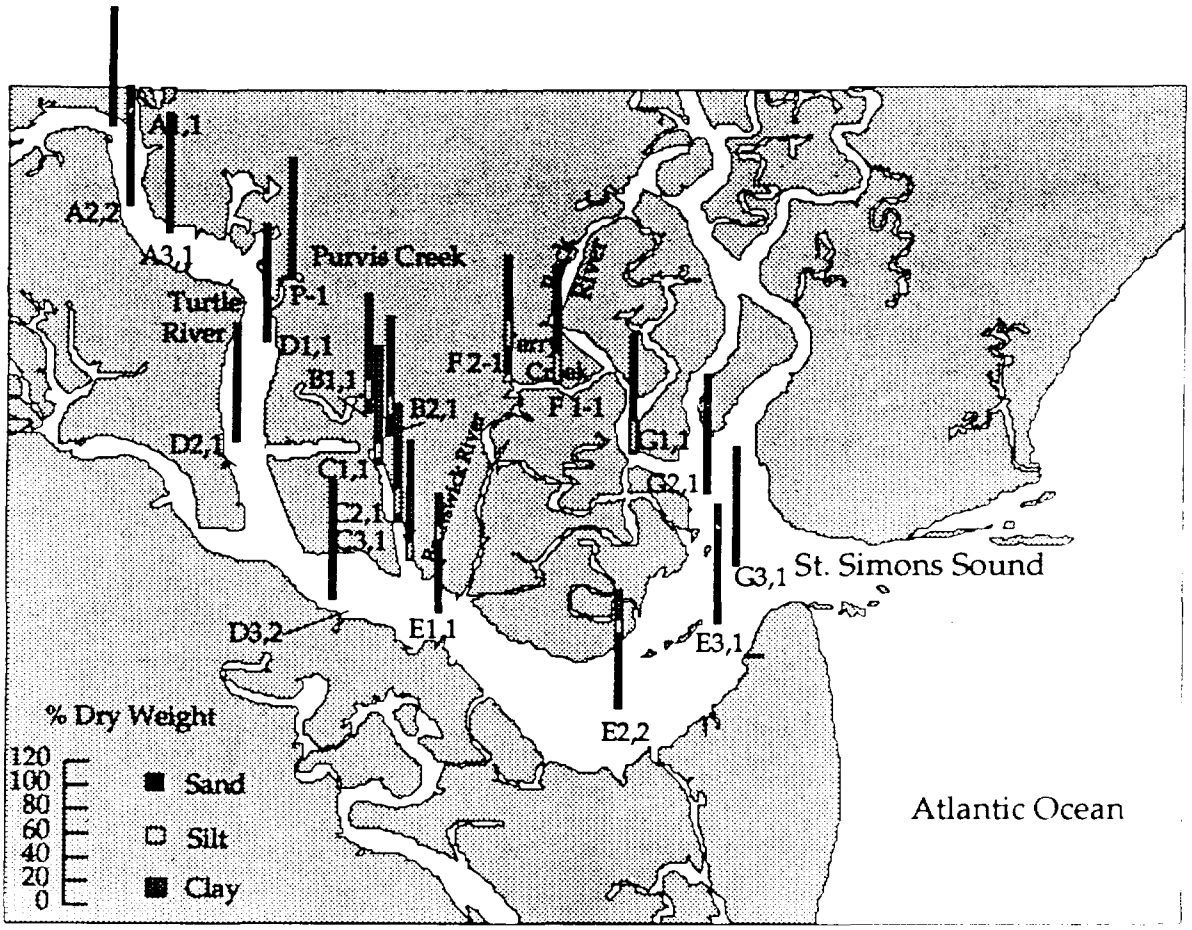


Figure 62. Concentrations of sand, silt, and clay in sediments from St. Simons Sound.

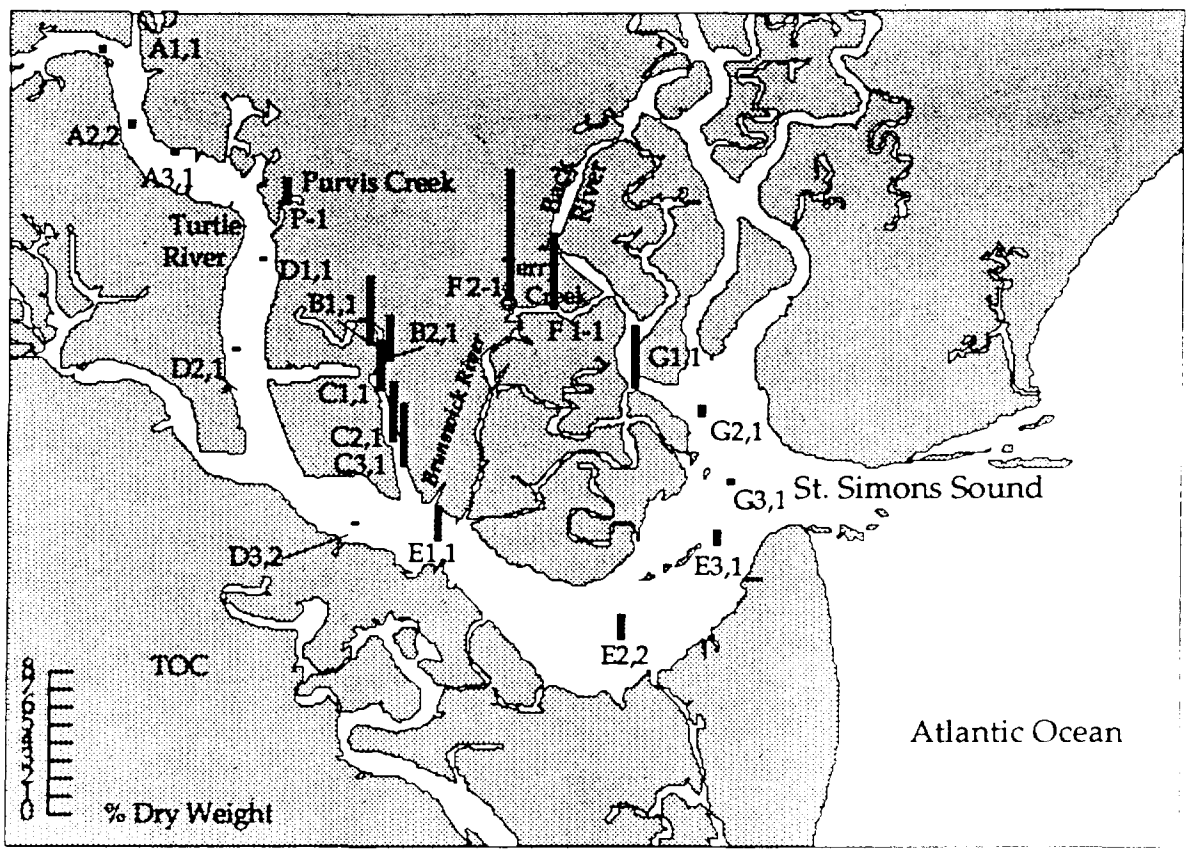


Figure 63. **Concentrations of total organic carbon in sediments from St. Simons Sound.**

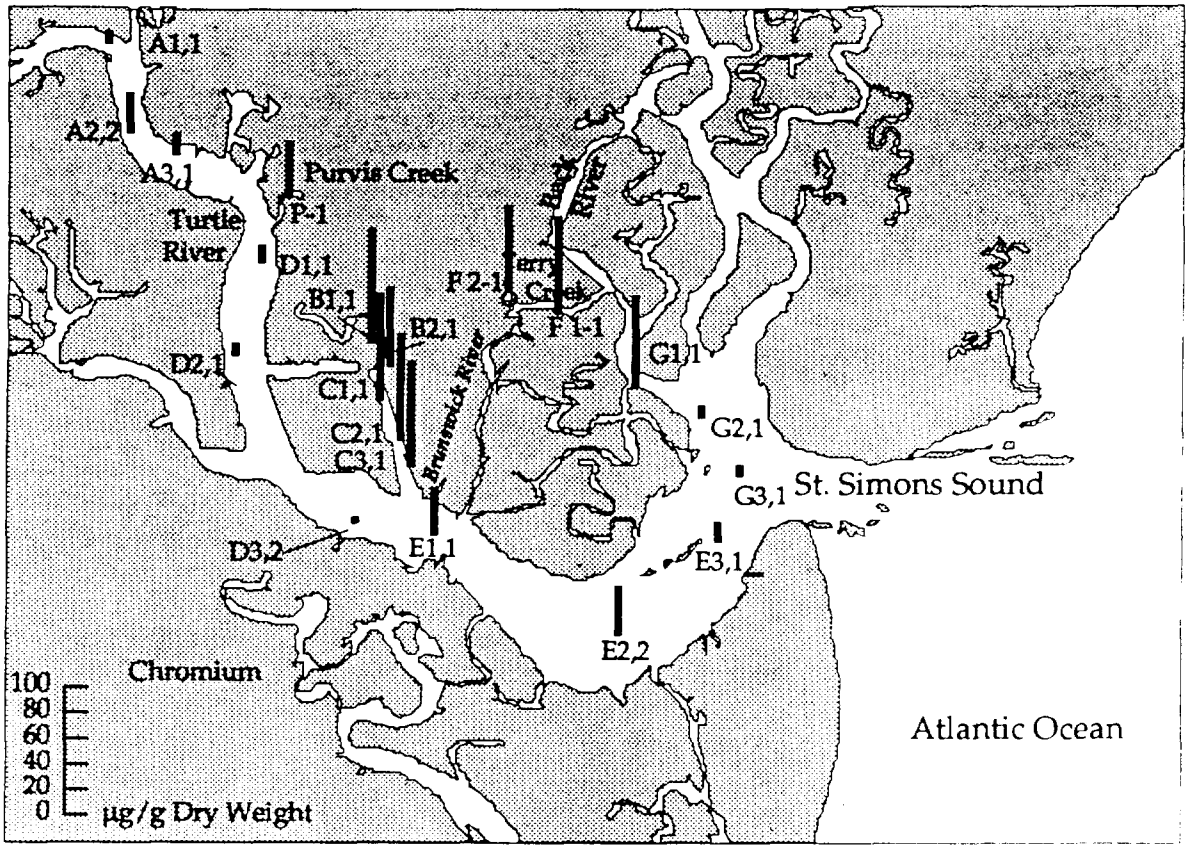


Figure 64. Concentrations of chromium in sediments from St. Simons Sound.

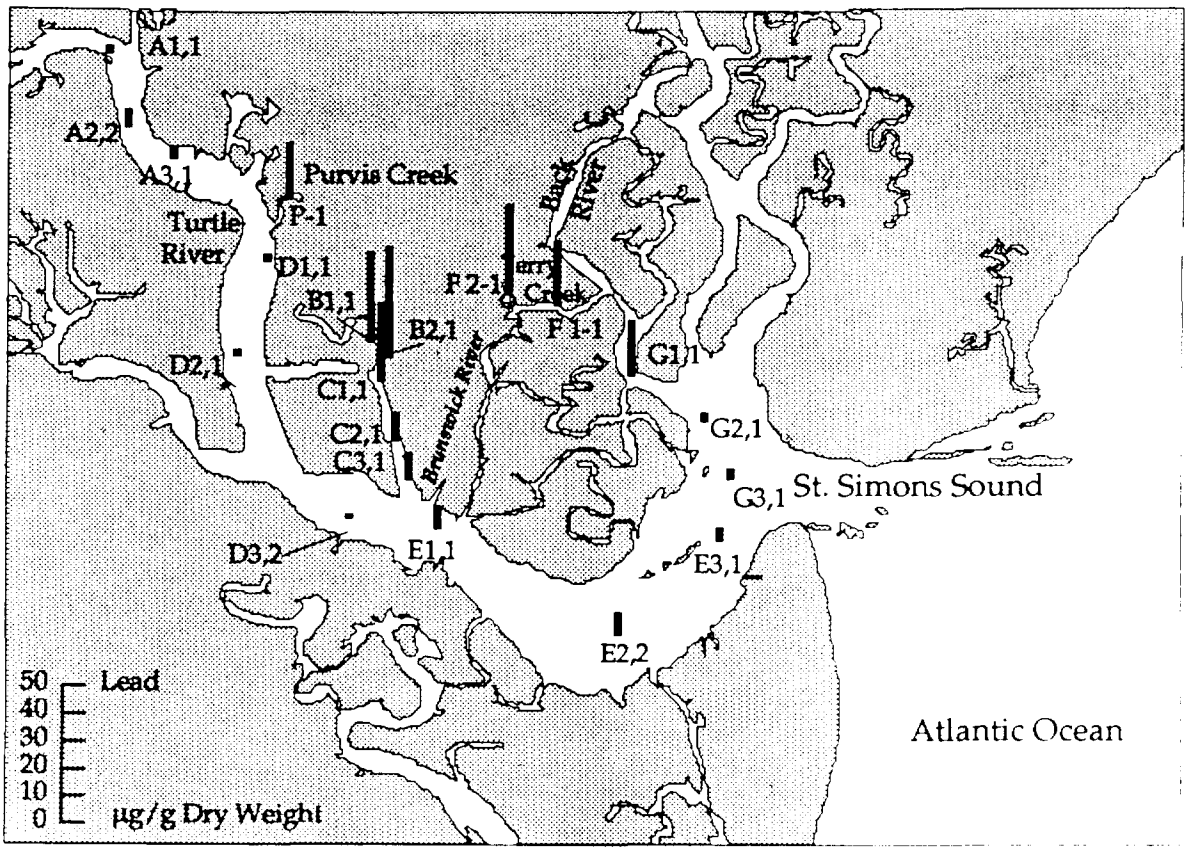


Figure 65. **Concentrations of lead in sediments from St. Simons Sound.**

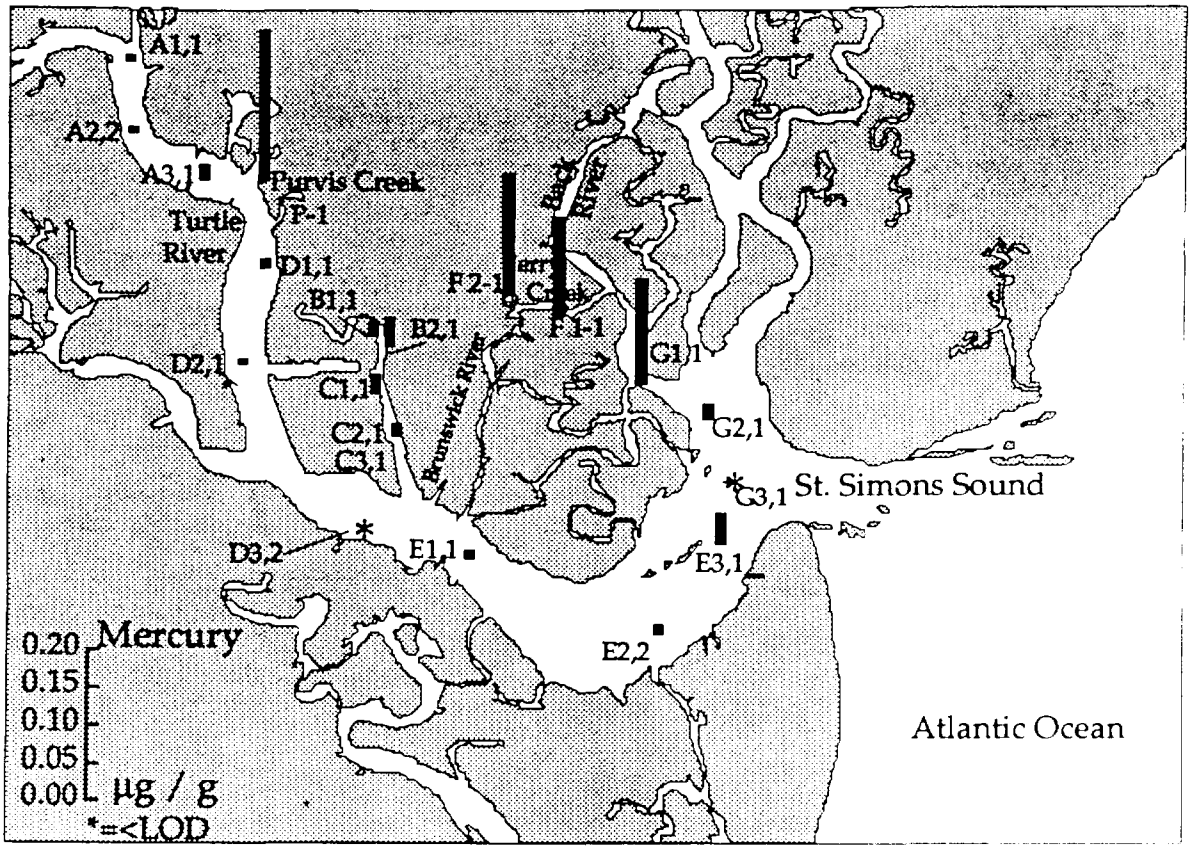


Figure 66. Concentrations of mercury in sediments from St. Simons Sound.

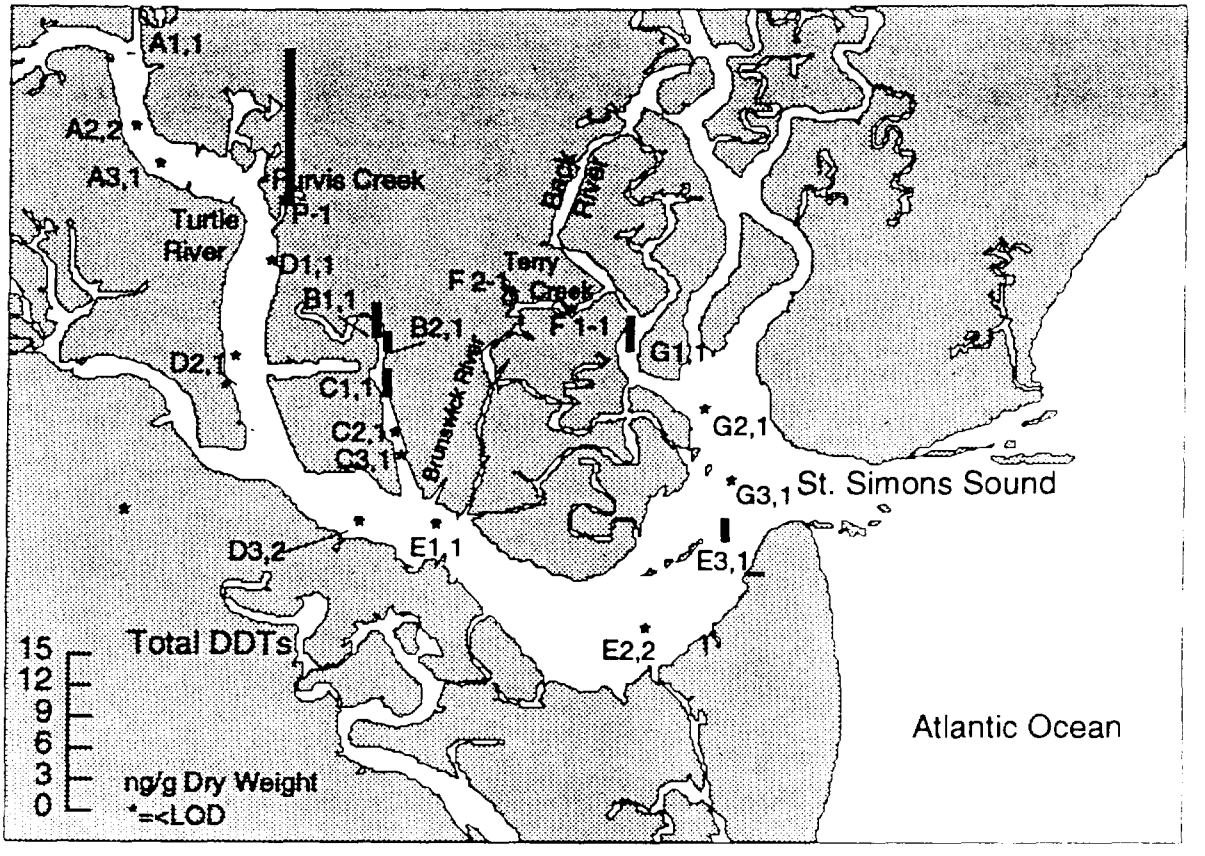


Figure 67. Concentrations of total DDTs in sediments from St. Simons Sound.

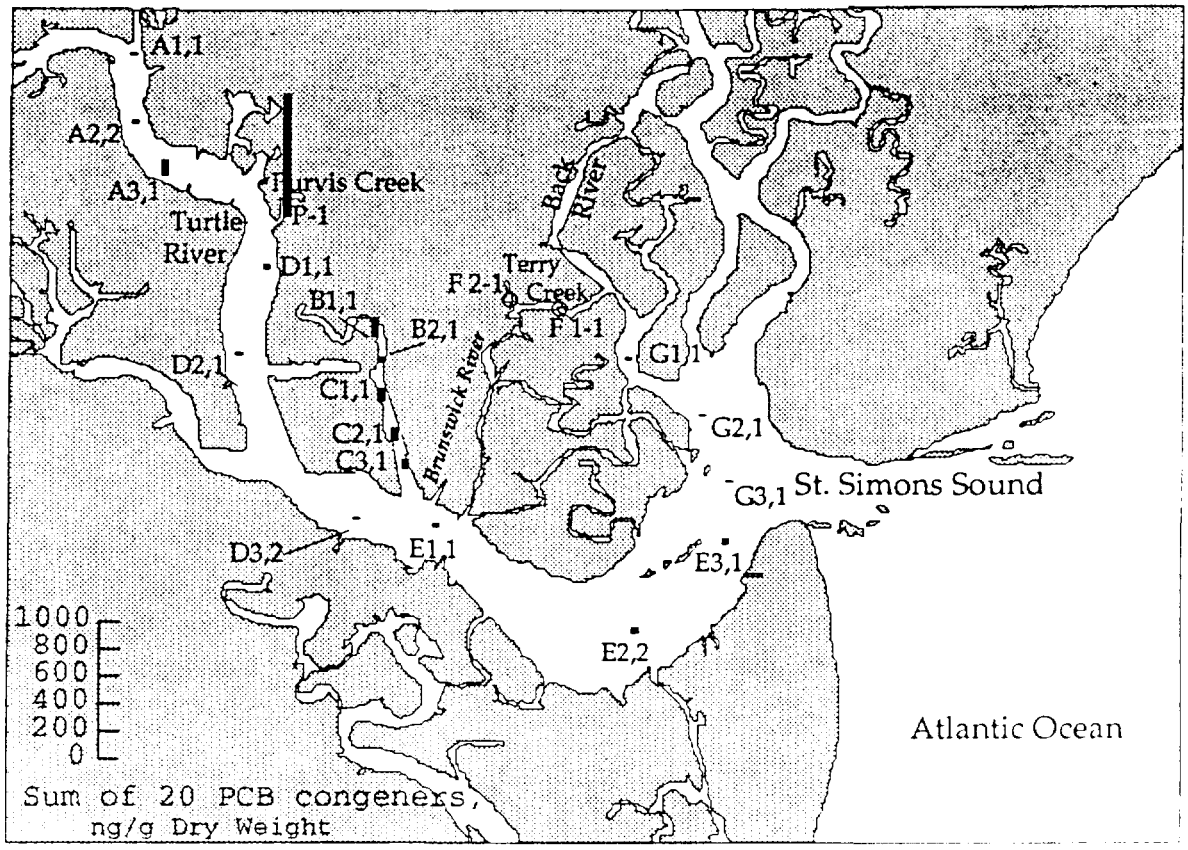


Figure 68. Concentrations of total PCBs (sum of 20 congeners) in sediments from St. Simons Sound.

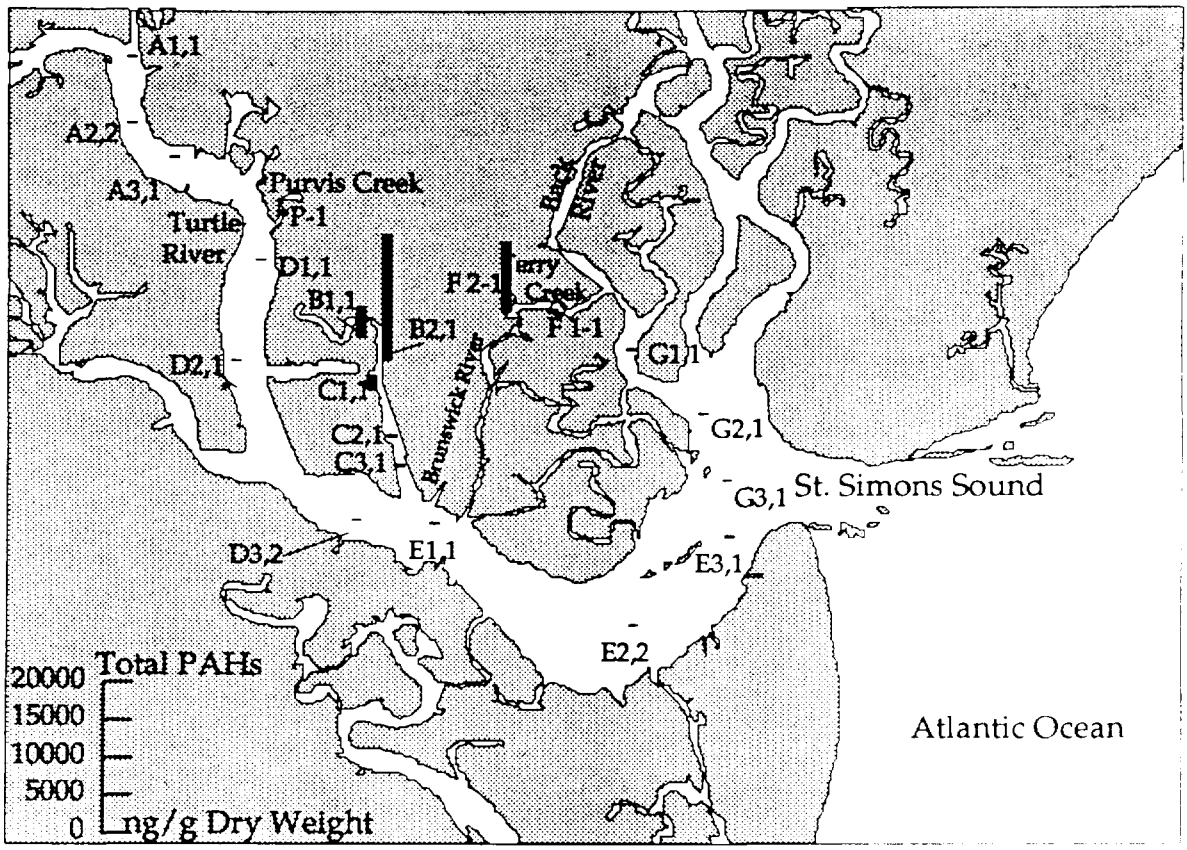


Figure 69. Concentrations of total PAHs in sediments from St. Simons Sound.

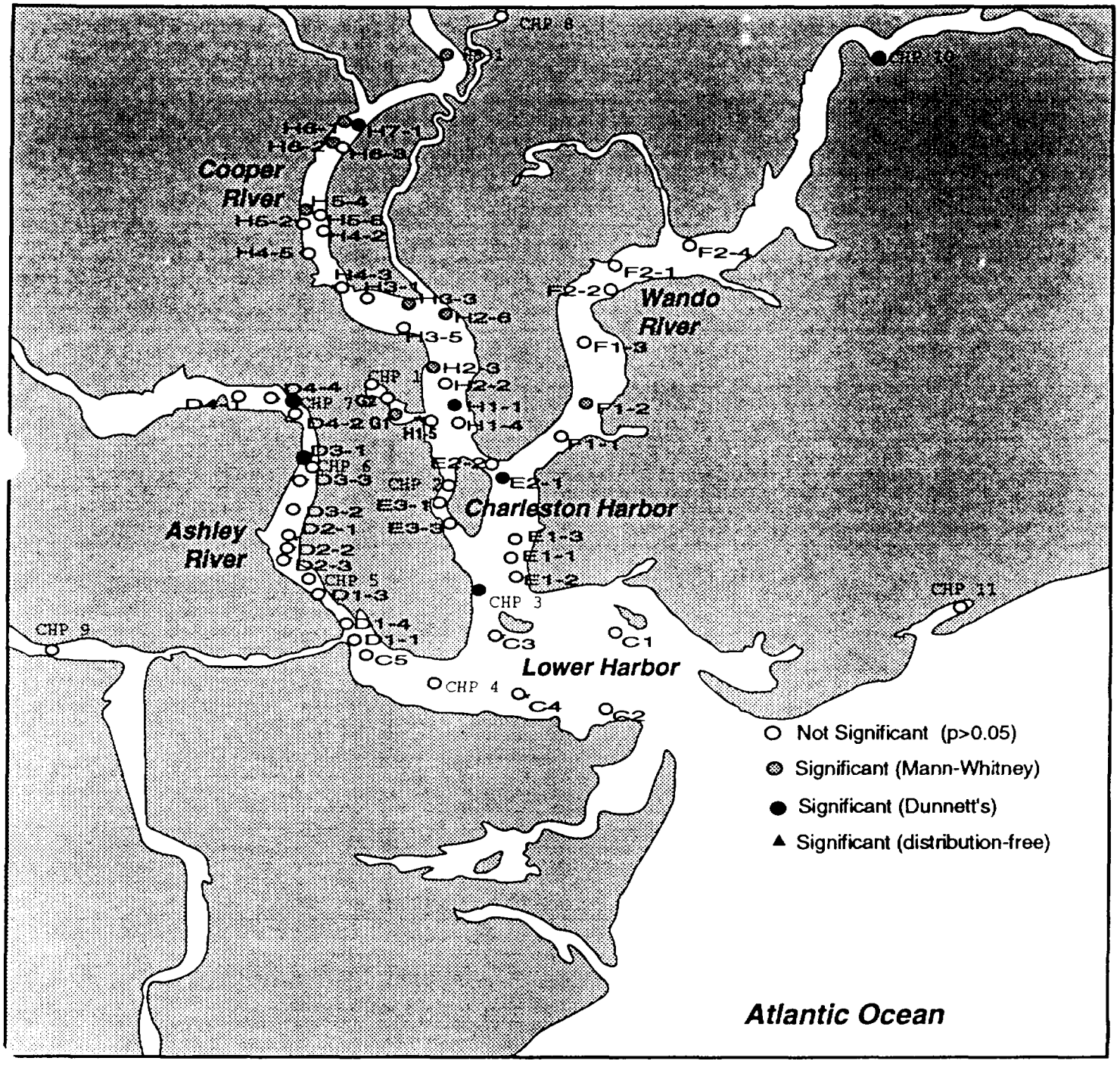


Figure 70. Distribution of Microtox test results in Charleston Harbor.

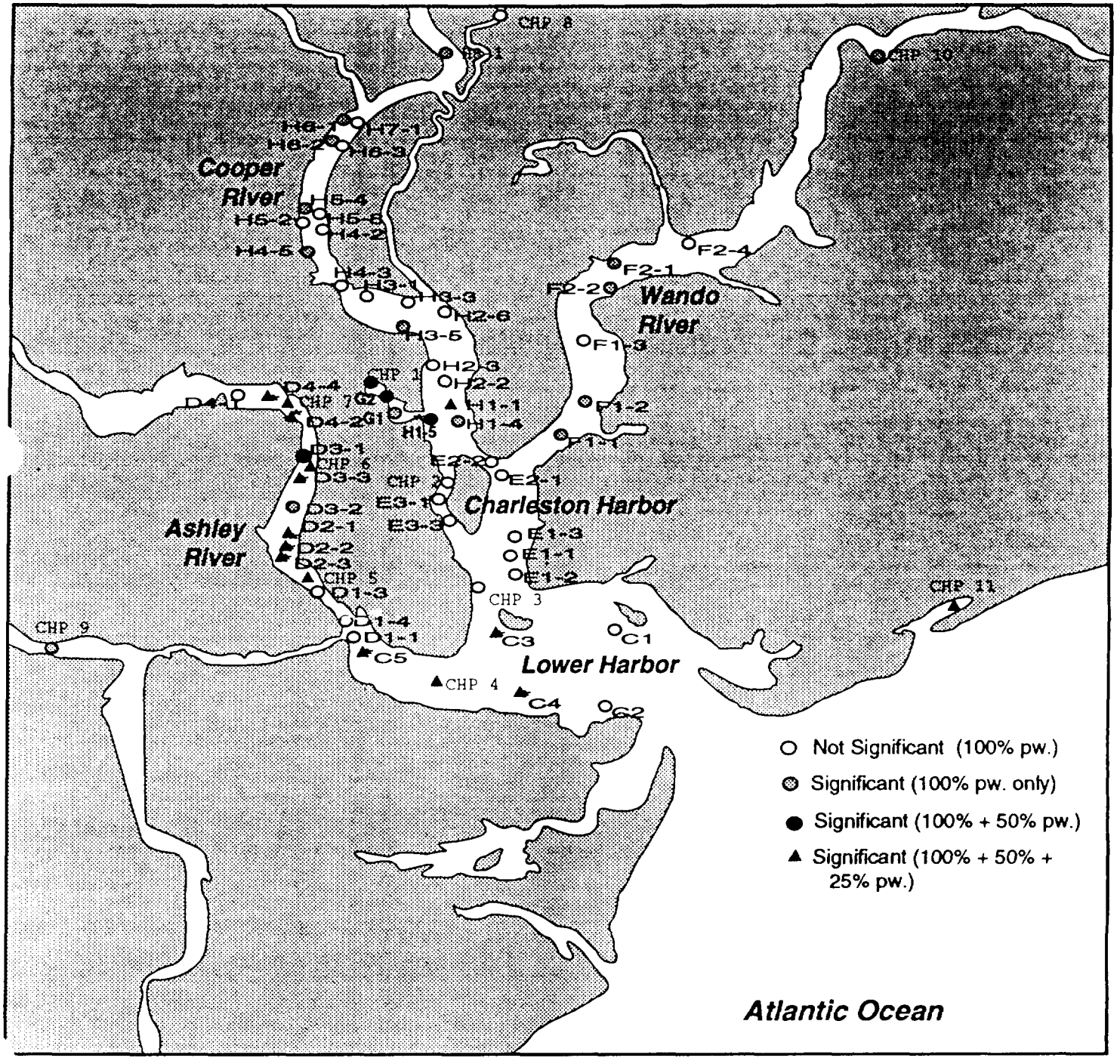


Figure 71. Distribution of results of urchin fertilization tests in 100%, 50%, and 25% porewater in Charleston Harbor.

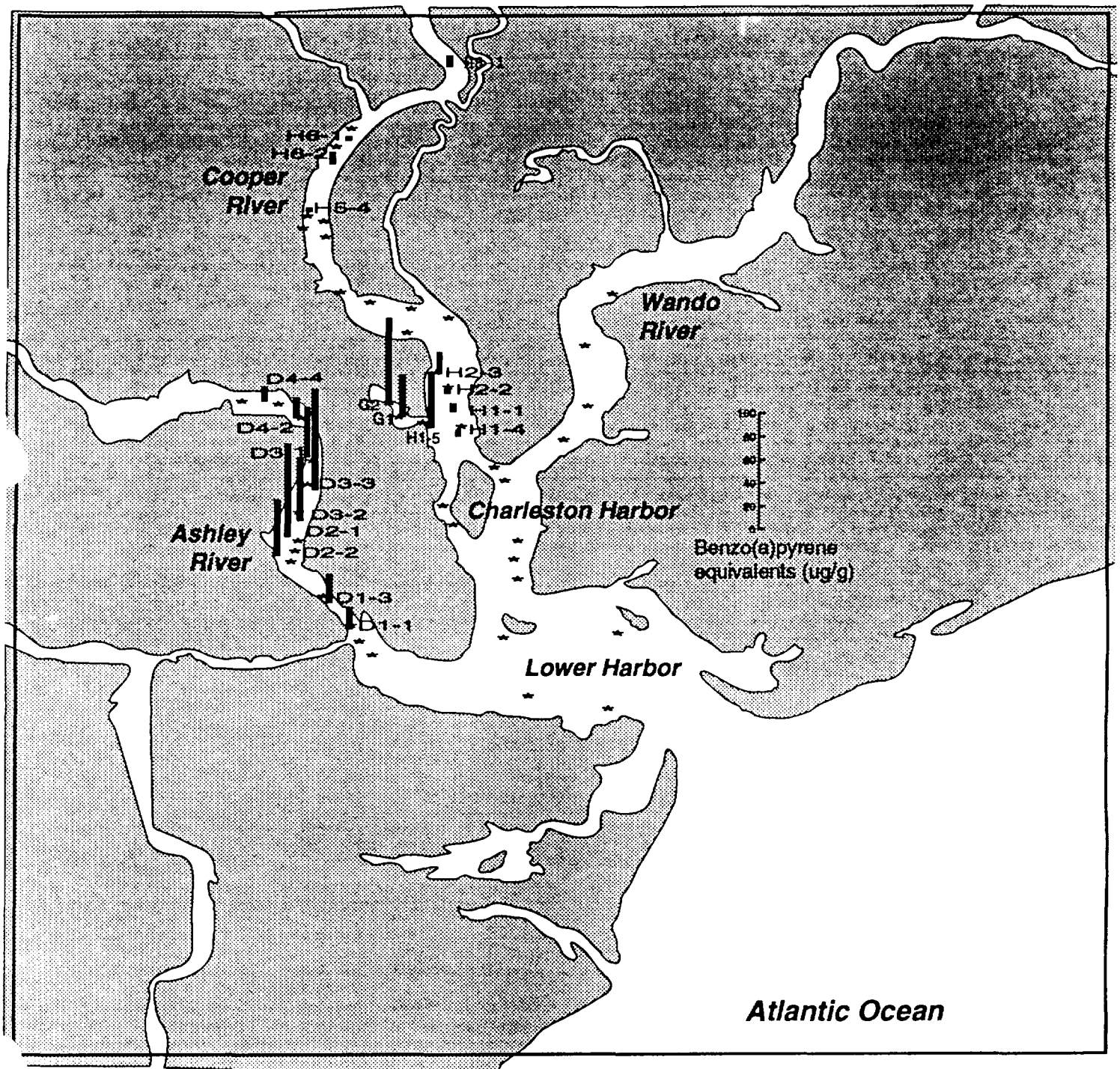


Figure 72. Results of cytochrome P-450 RGS assays of selected sediment samples from Charleston Harbor (ave. benzo(a)pyrene equivalents, ug/g).

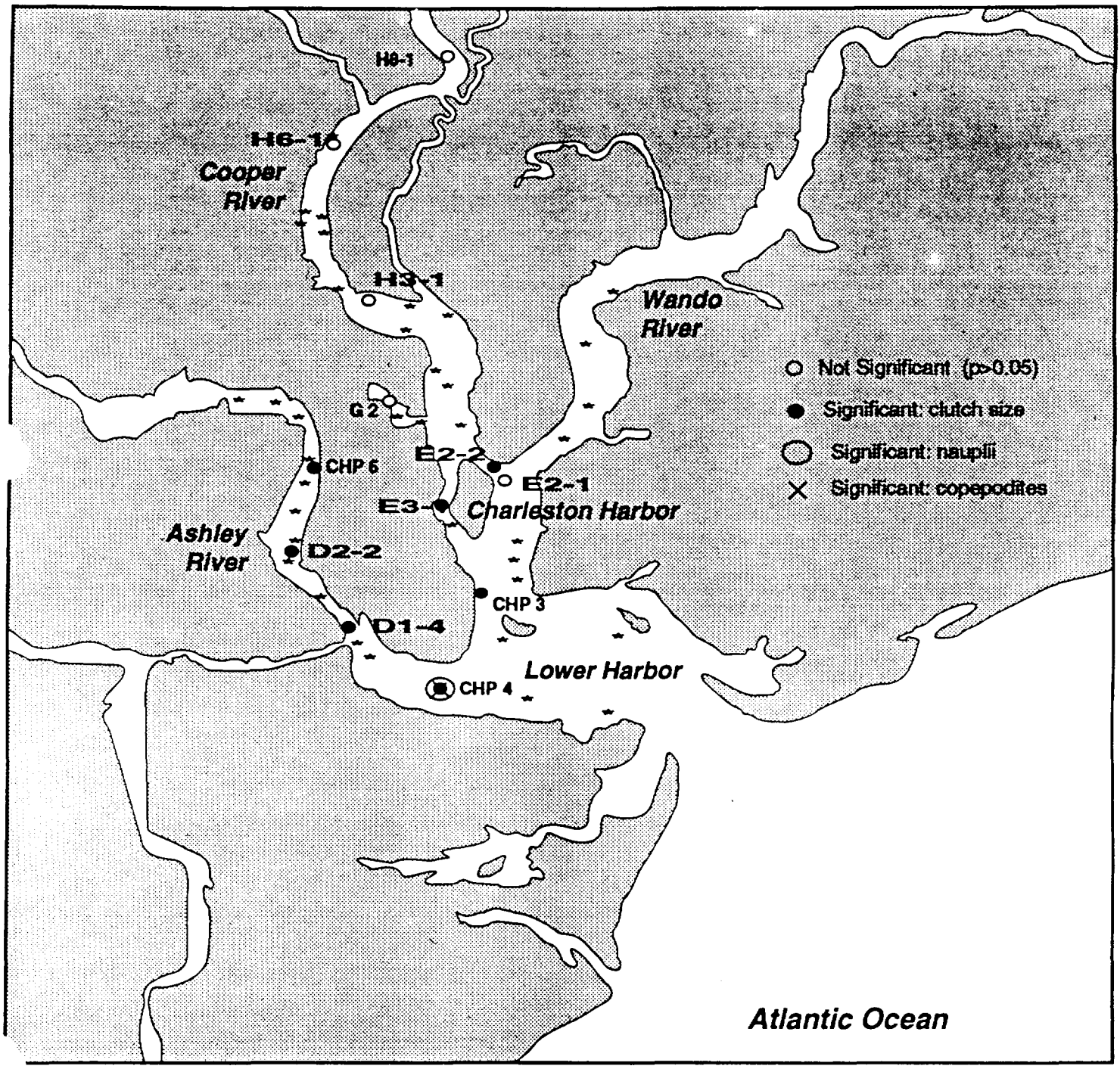


Figure 73. Distribution of copepod reproduction test results in Charleston Harbor.

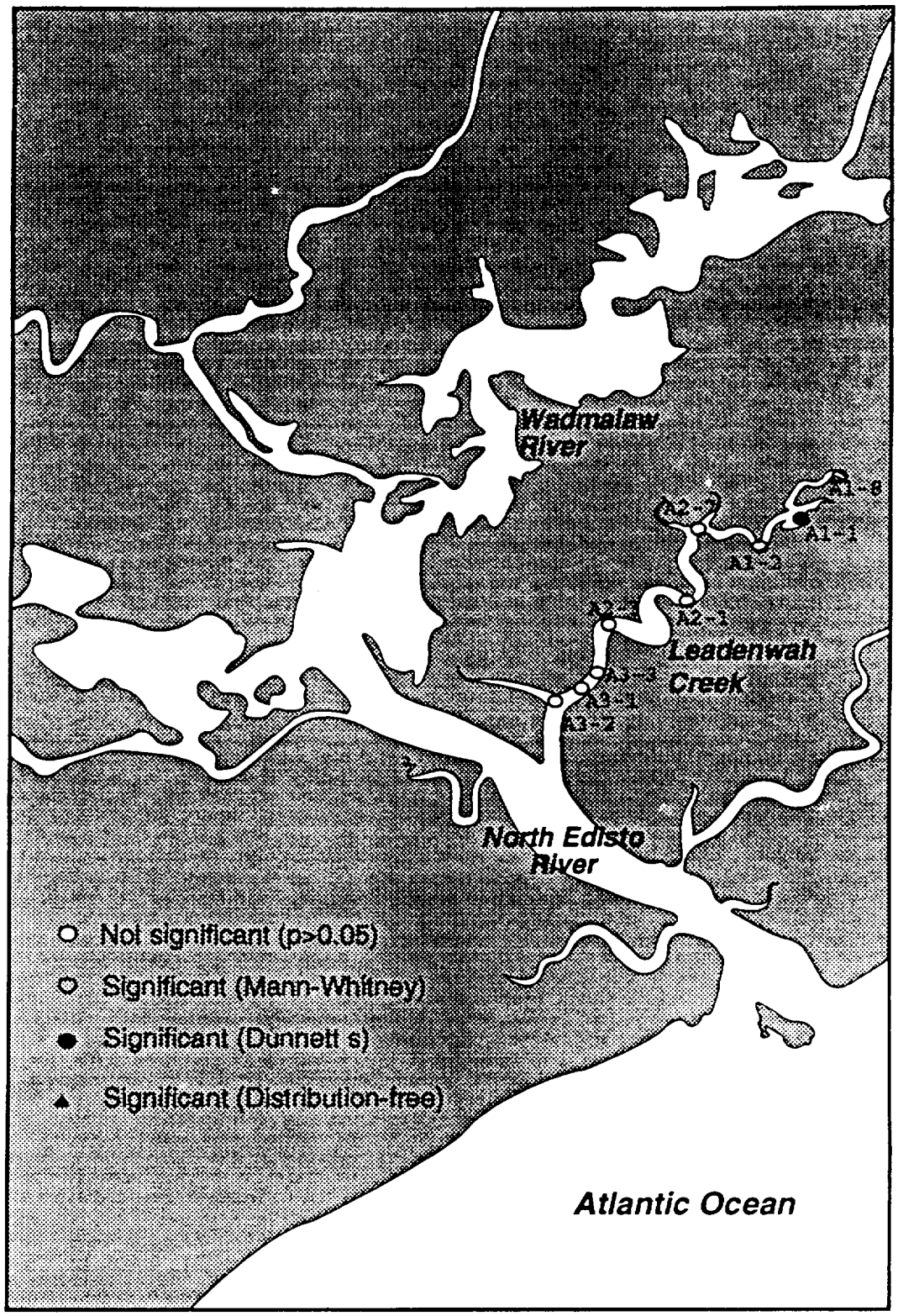


Figure 74. Distribution of Microtox test results in Leadenwah Creek.

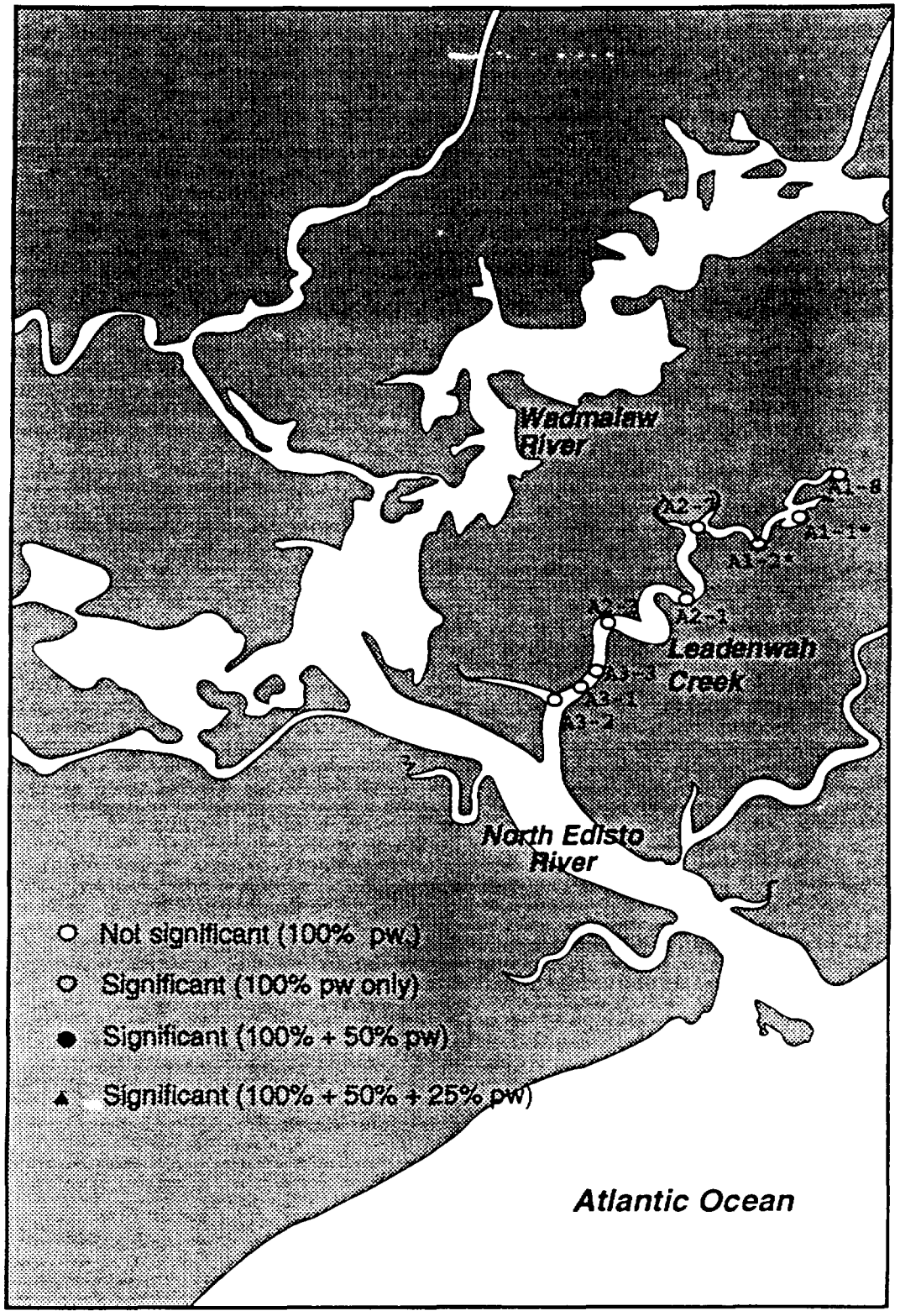


Figure 75. Distribution of urchin fertilization test results in Leadenwah Creek.
(* significant results observed in 25% porewater only).

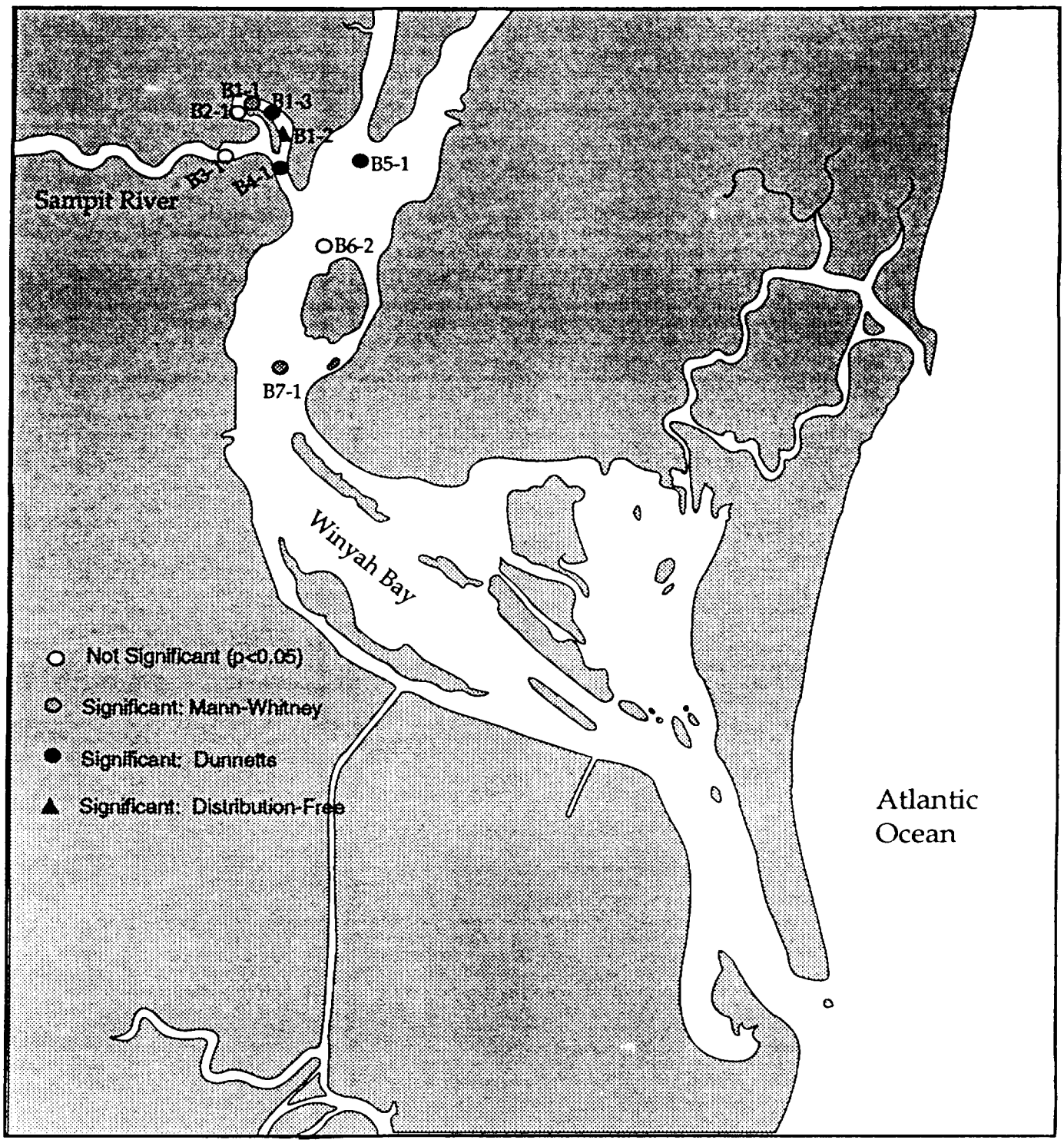


Figure 76. Distribution of Microtox test results for Winyah Bay.

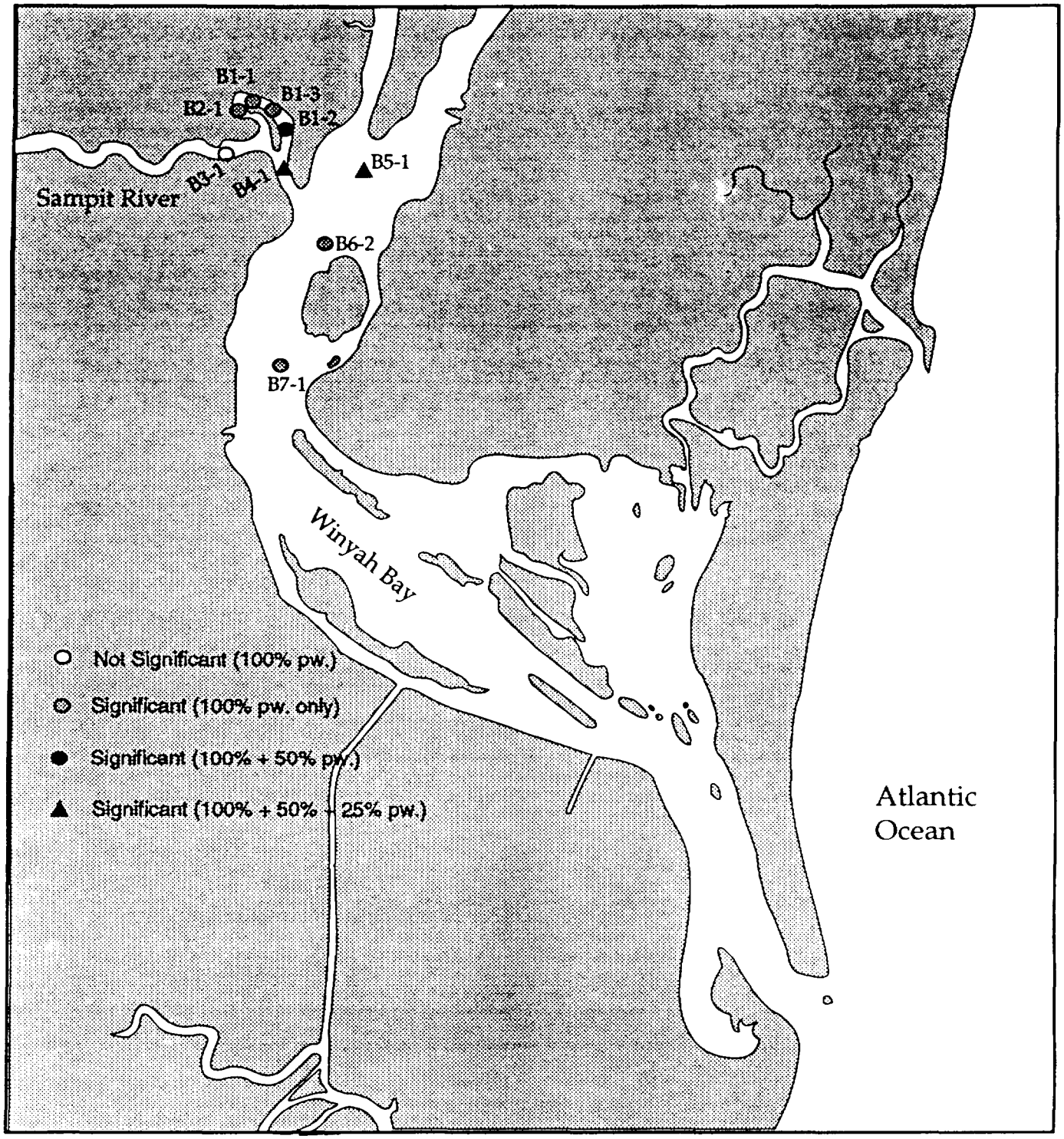


Figure 77. Distribution of results of urchin fertilization tests in 100%, 50%, and 25% porewater in Winyah Bay.

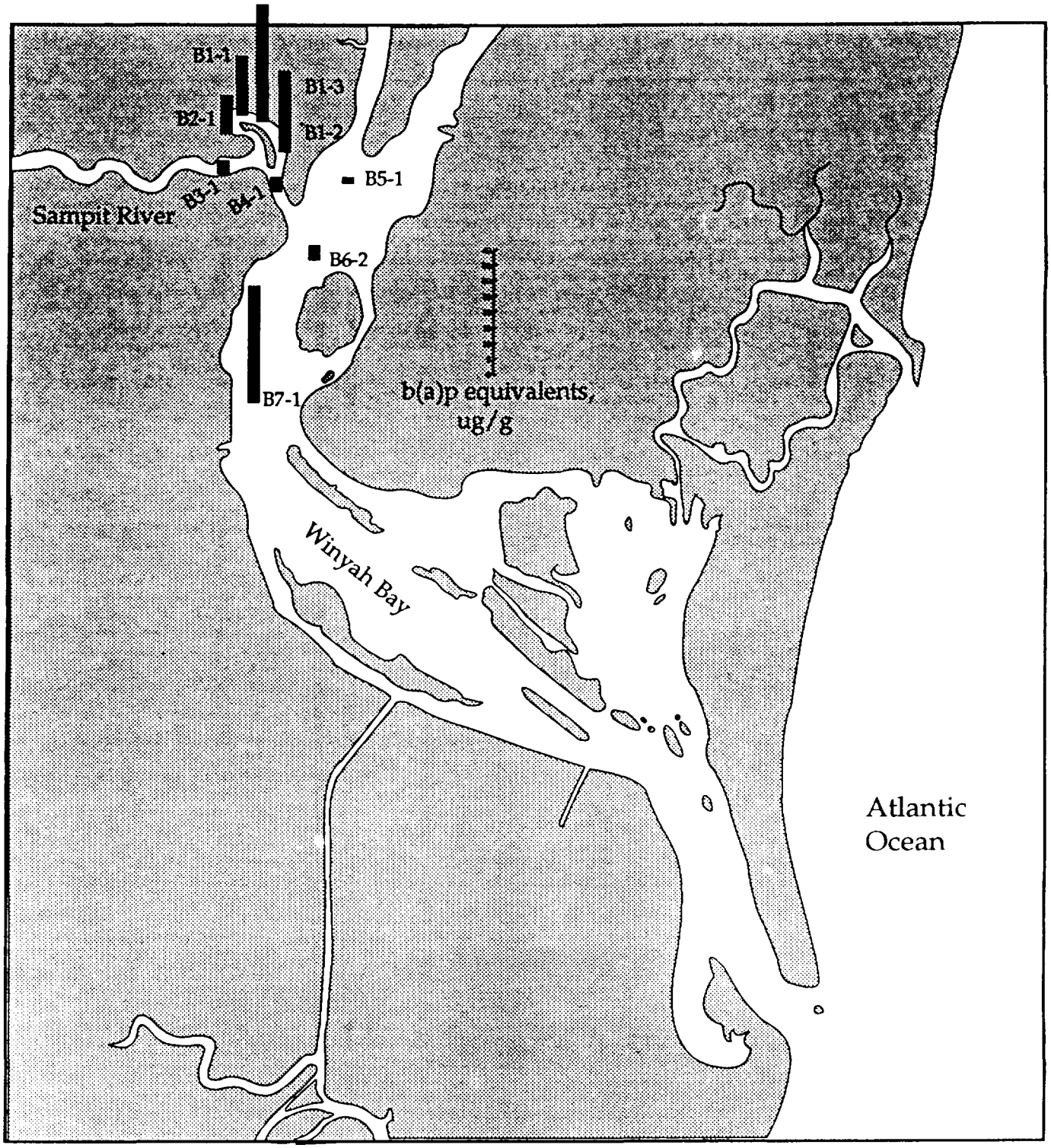


Figure 78. Results of cytochrome P-450 RGS assays of selected sediment samples from Winyah Bay (benzo(a)pyrene equivalents, ug/g).

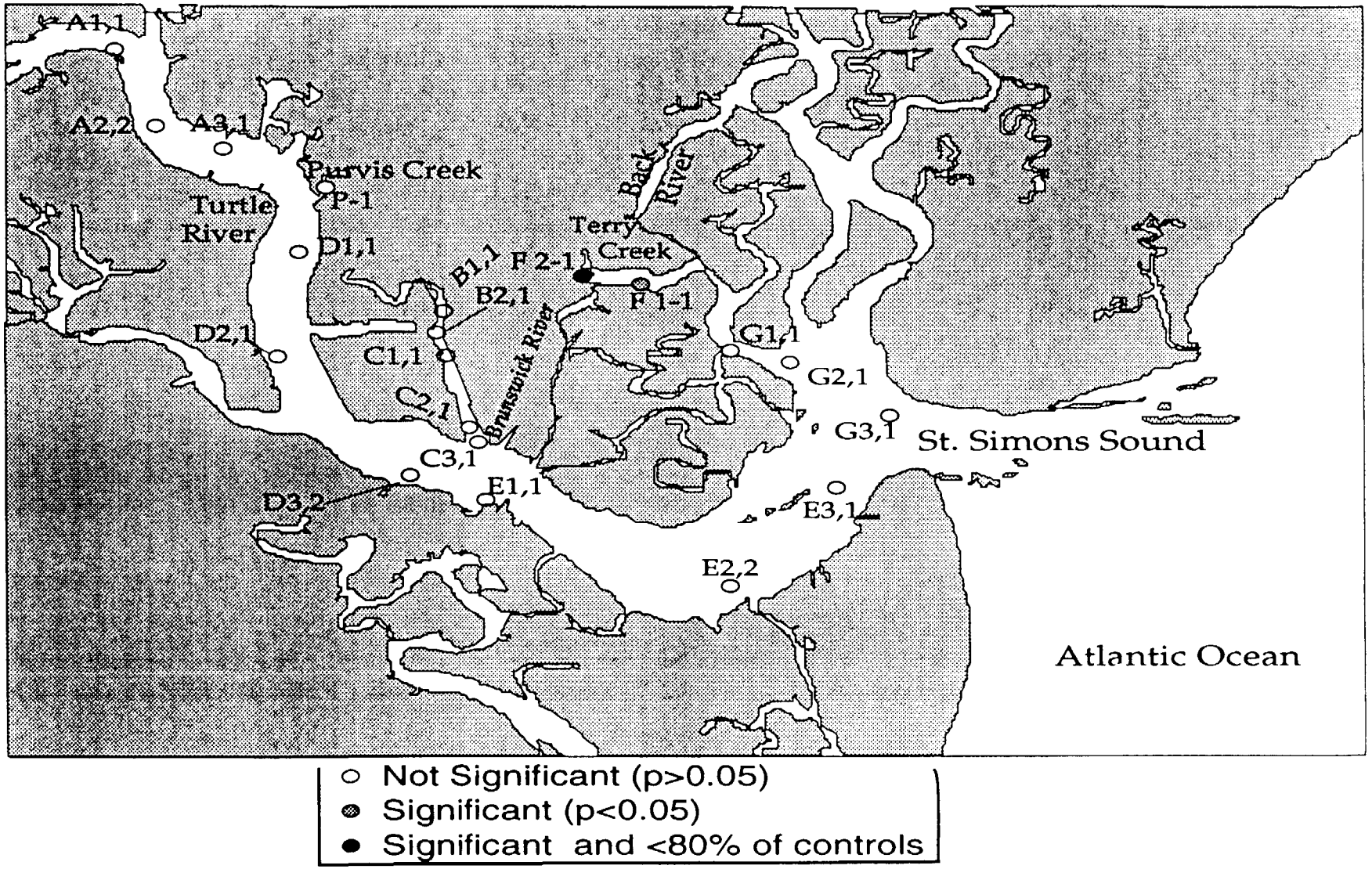


Figure 79. Distribution of amphipod test results in St. Simons Sound.

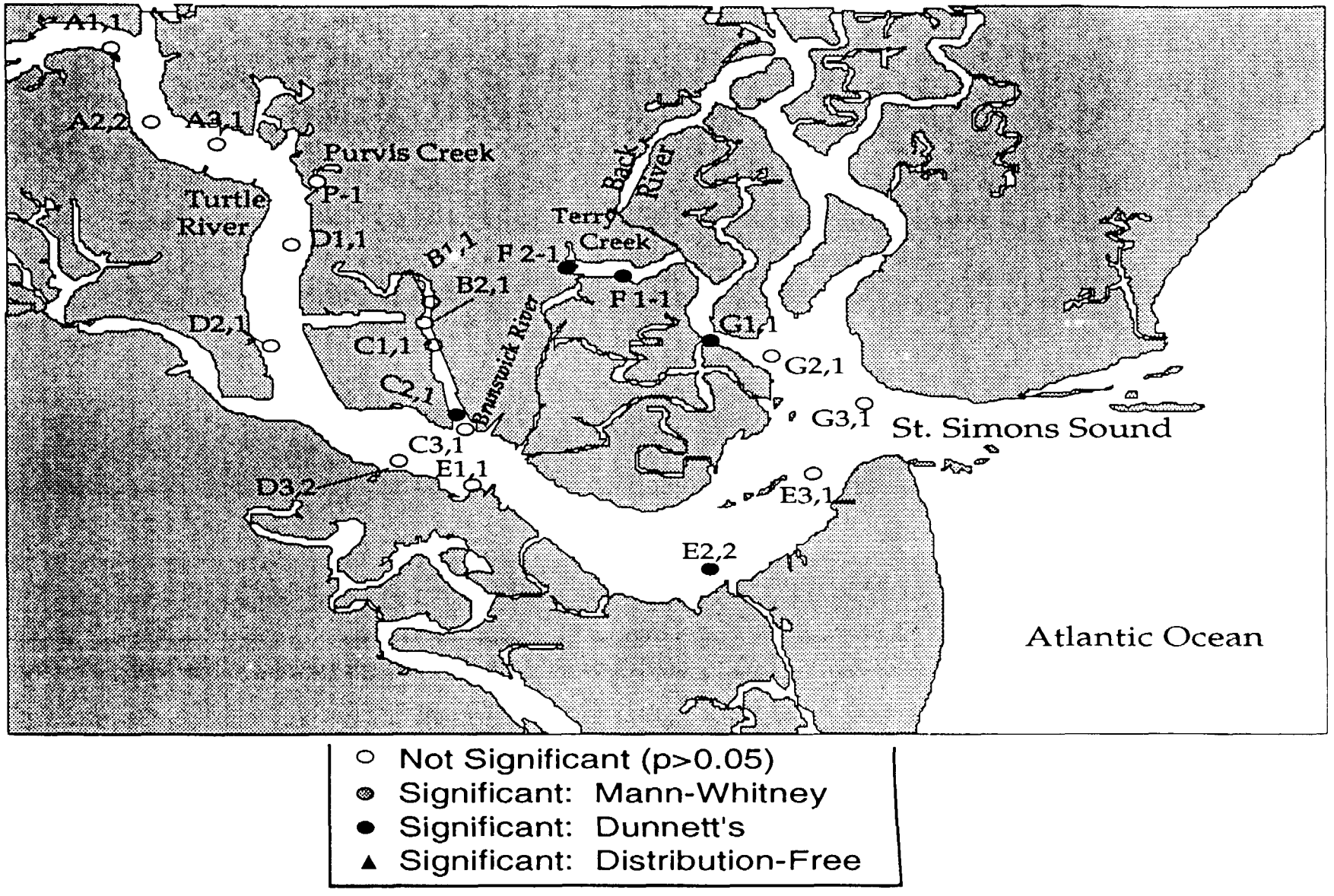


Figure 80. Distribution of Microtox test results in St. Simons Sound.

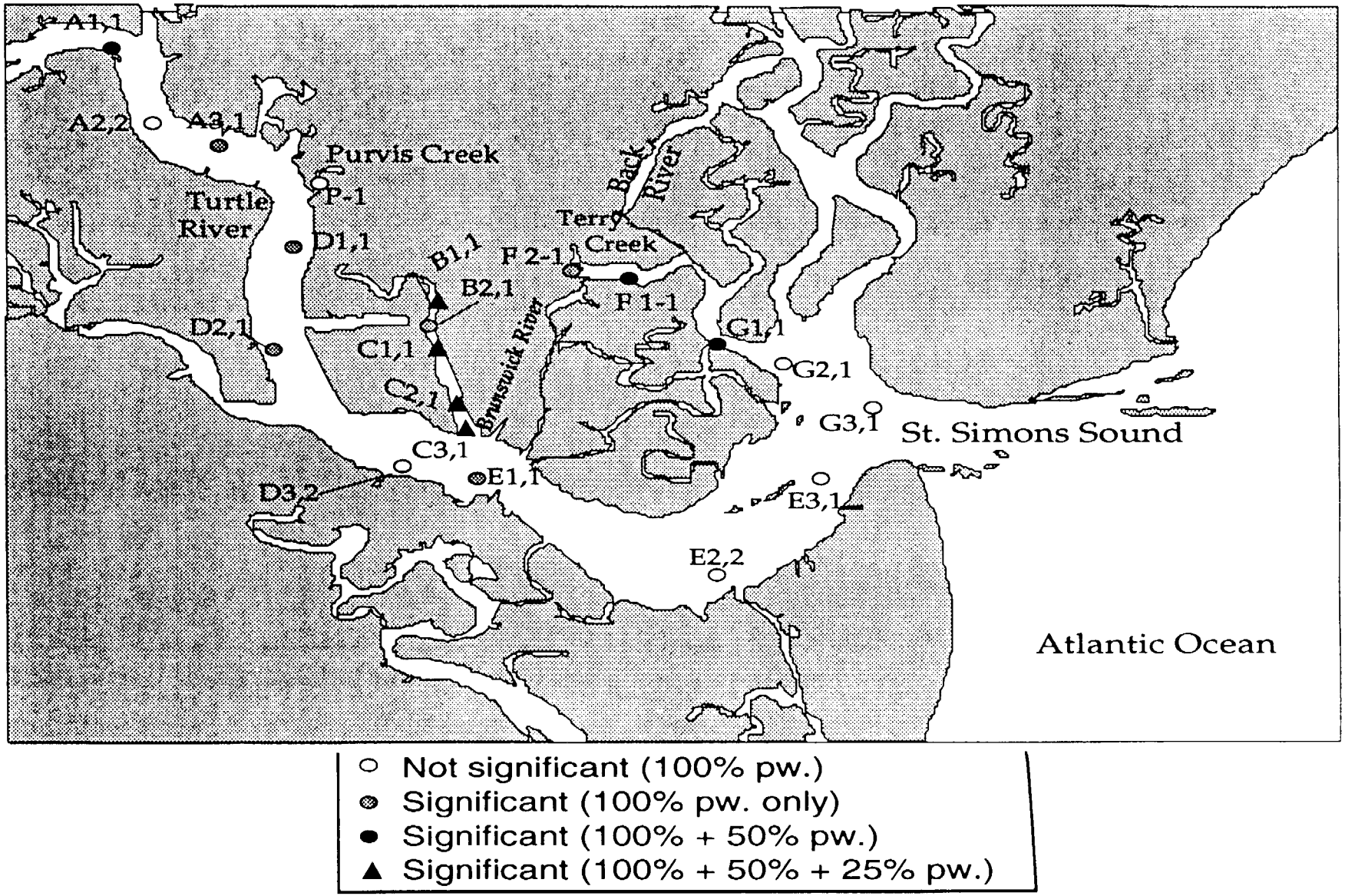


Figure 81. Distribution of urchin embryological development test results in St. Simons Sound.

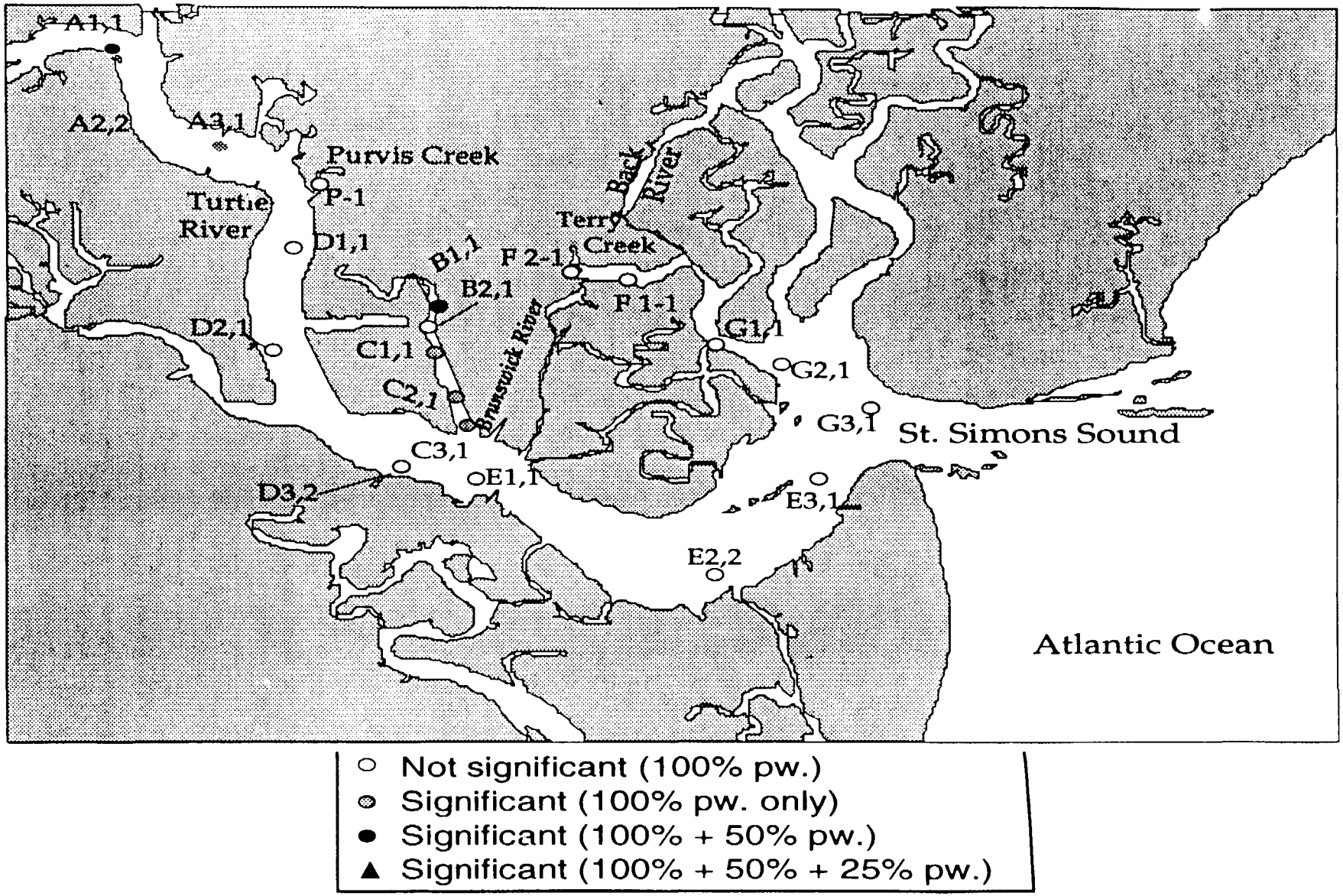


Figure 82. Distribution of urchin egg fertilization test results in St. Simons Sound.

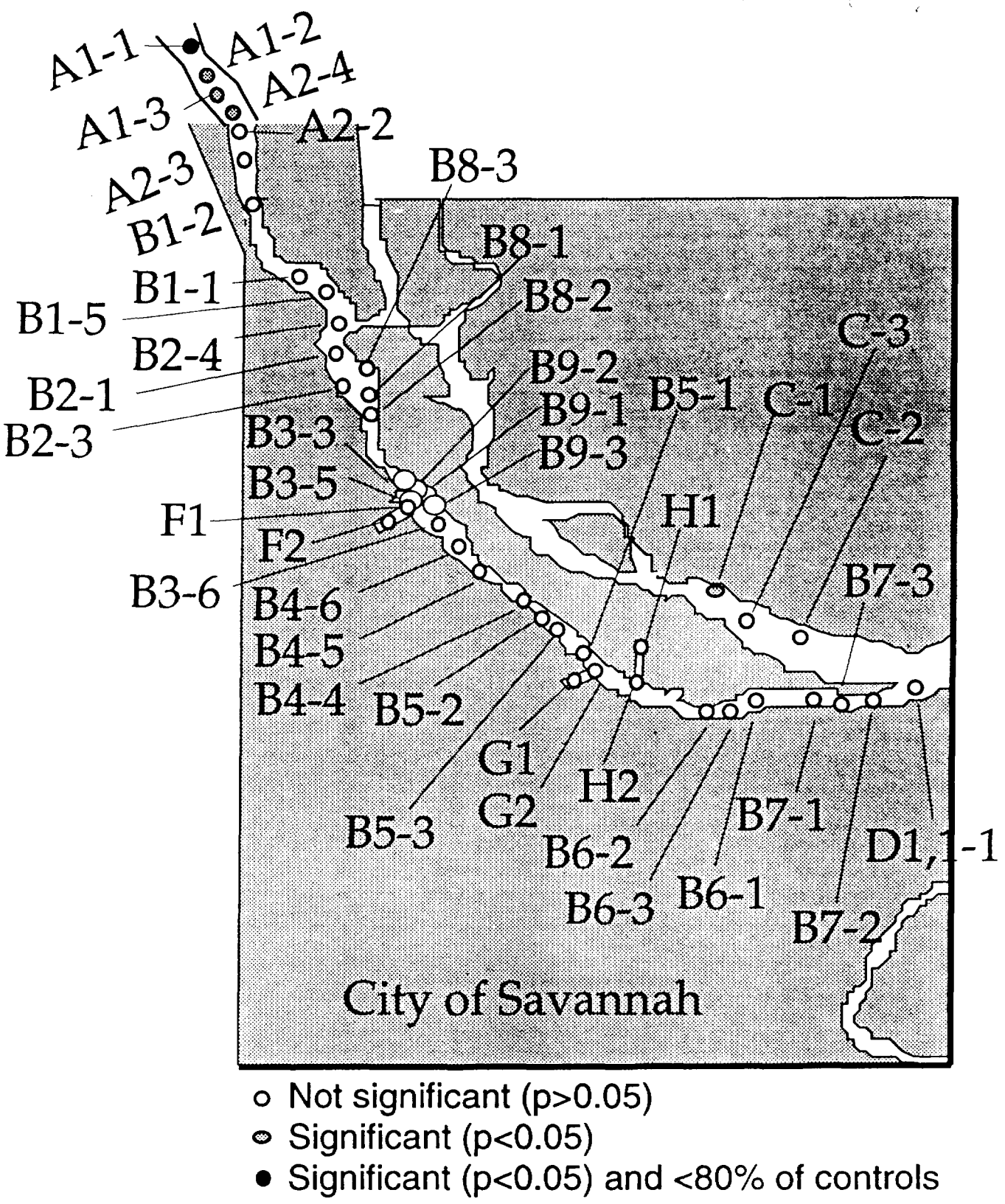


Figure 83. Distribution of amphipod test results in the upper Savannah River.

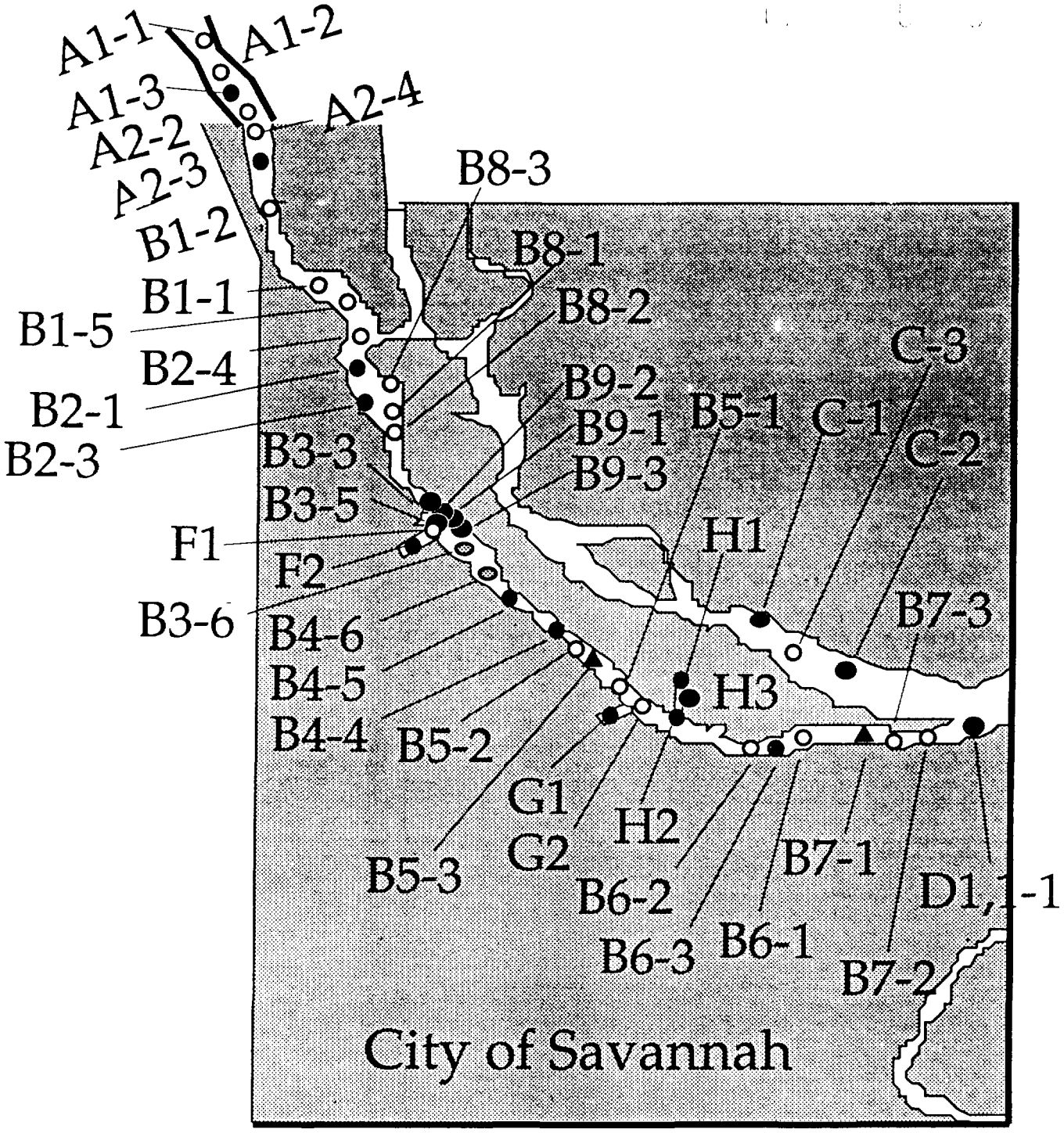


Figure 84. Distribution of Microtox test results in the upper Savannah River.

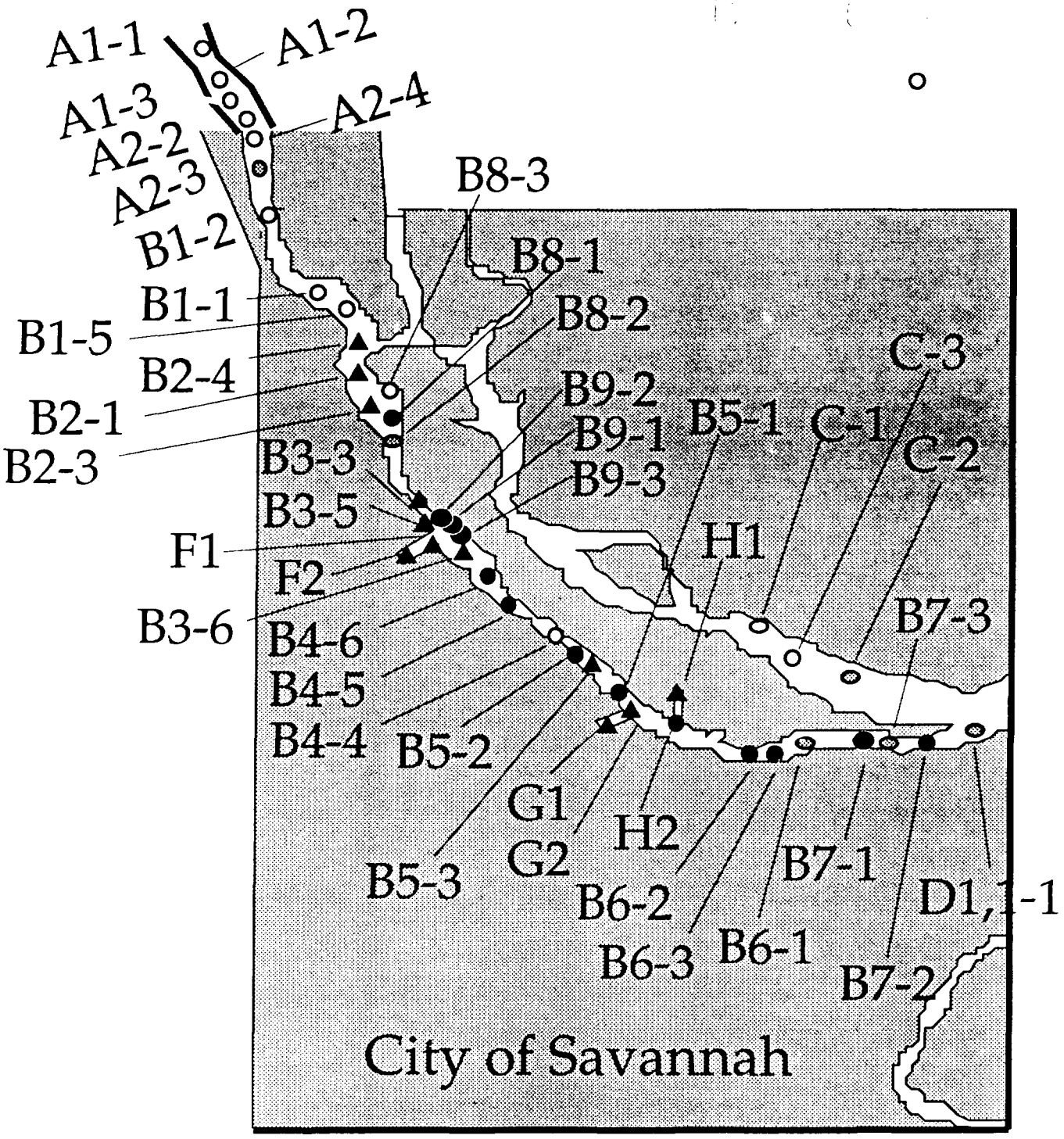


Figure 85. Distribution of urchin embryological development test results in the upper Savannah River.

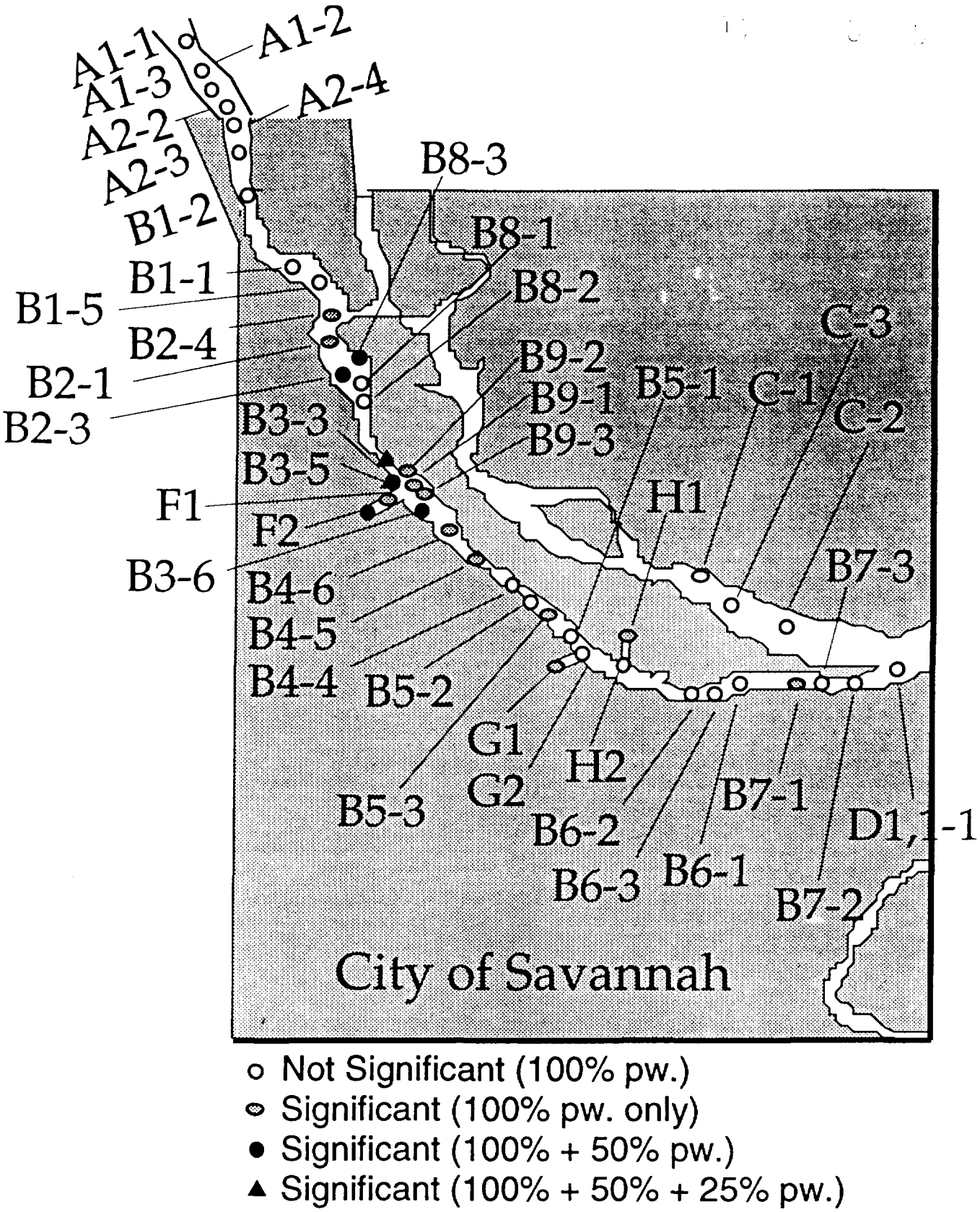
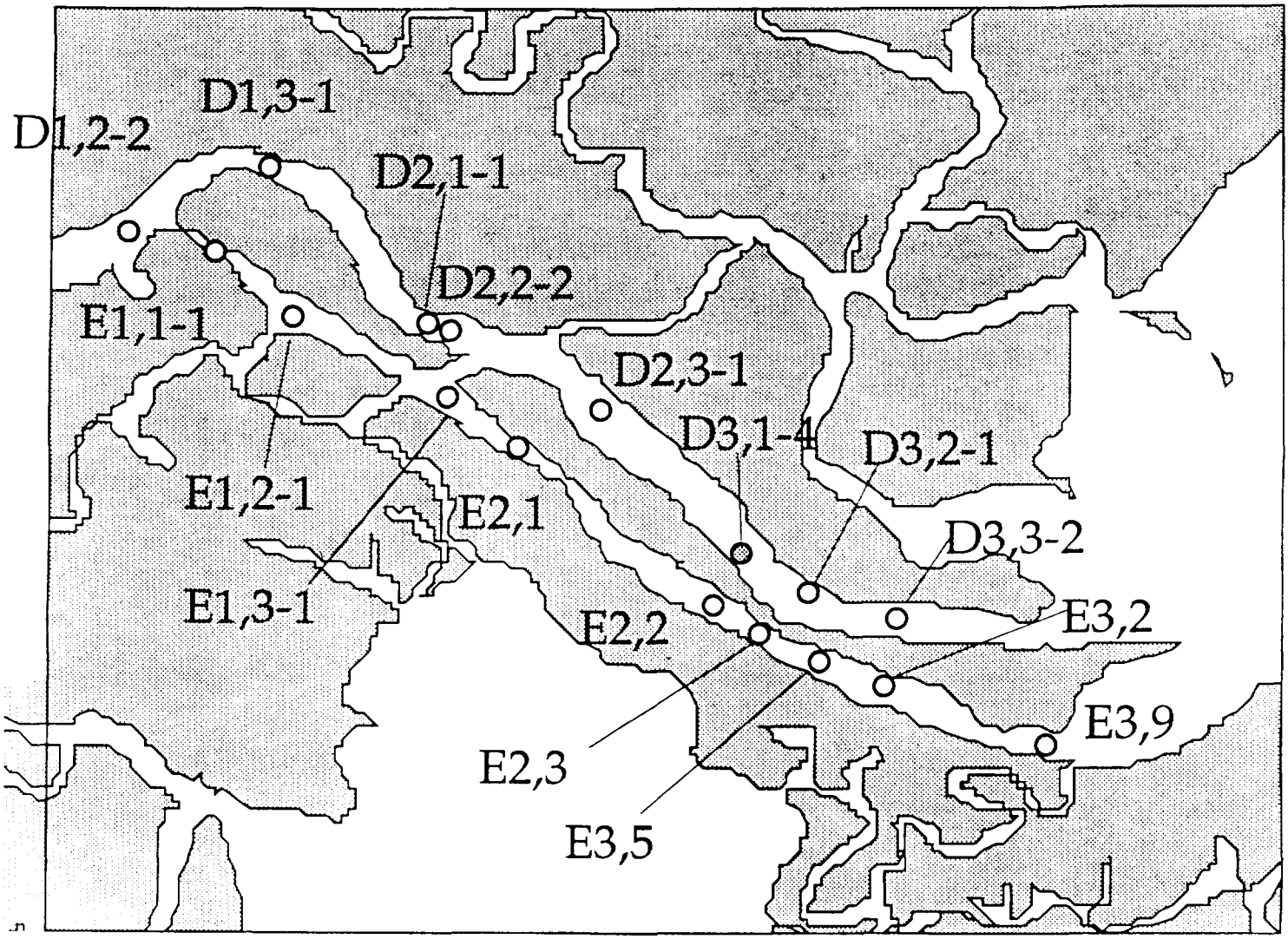


Figure 86. Distribution of urchin egg fertilization test results in the upper Savannah River.



○ Not significant (p>0.05)
○ Significant (p<0.05)
● Significant (p<0.05) and < 80% of control

Figure 87. Distribution of amphipod test results in the lower Savannah River.

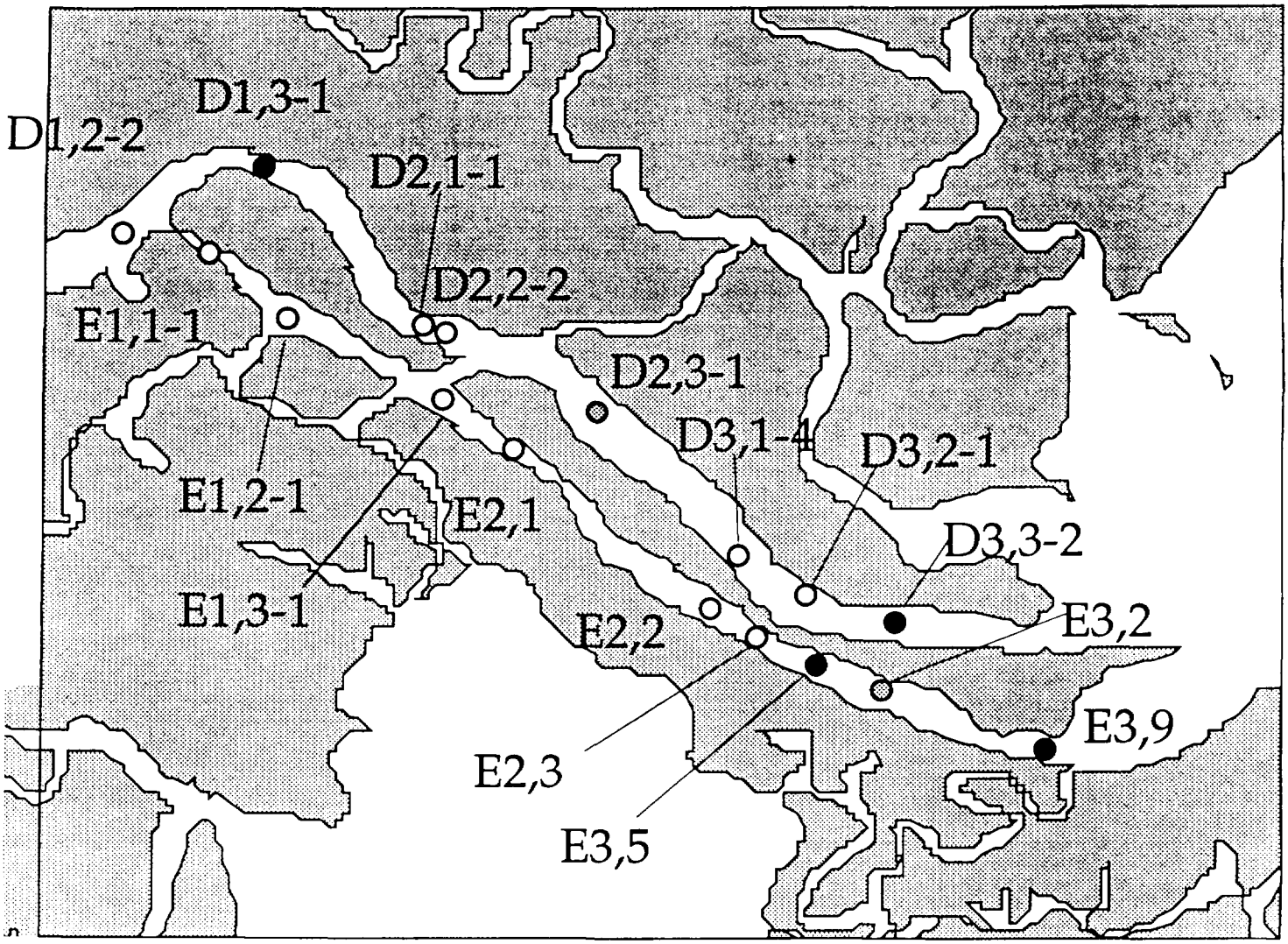


Figure 88. Distribution of Microtox test results in the lower Savannah River.

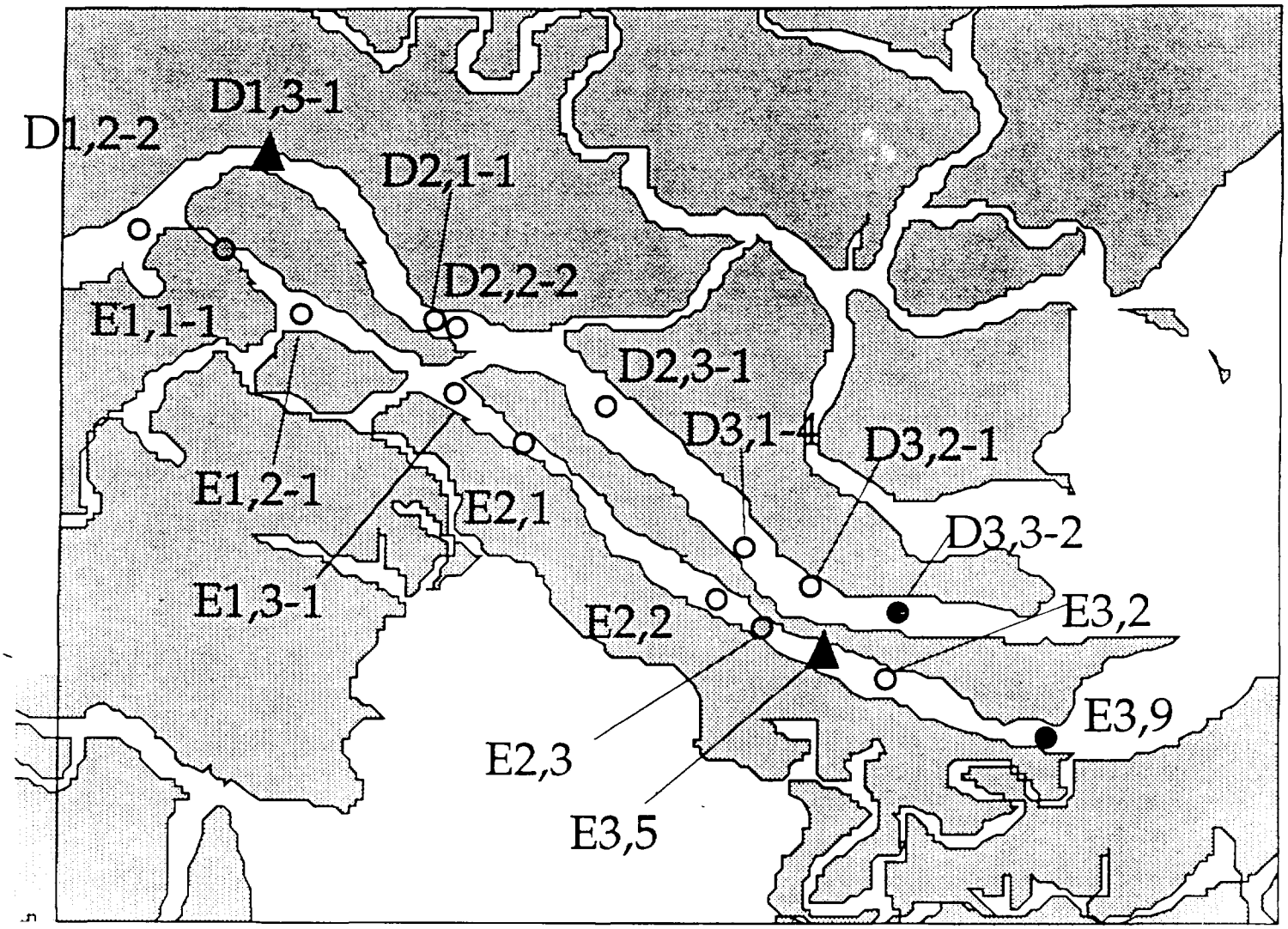


Figure 89. Distribution of urchin embryological development test results in the lower Savannah River.

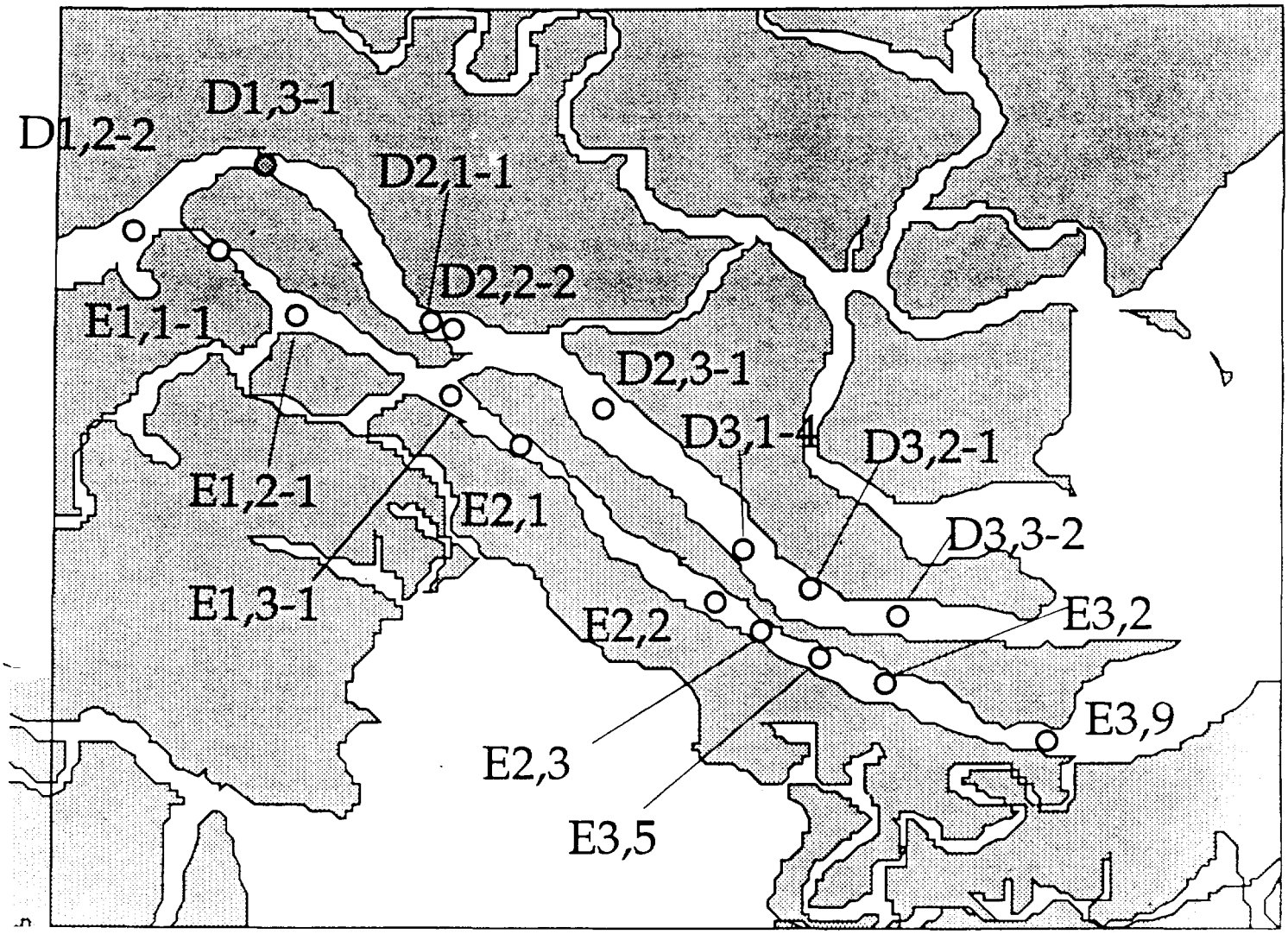


Figure 90. Distribution of urchin egg fertilization test results in the lower Savannah River.

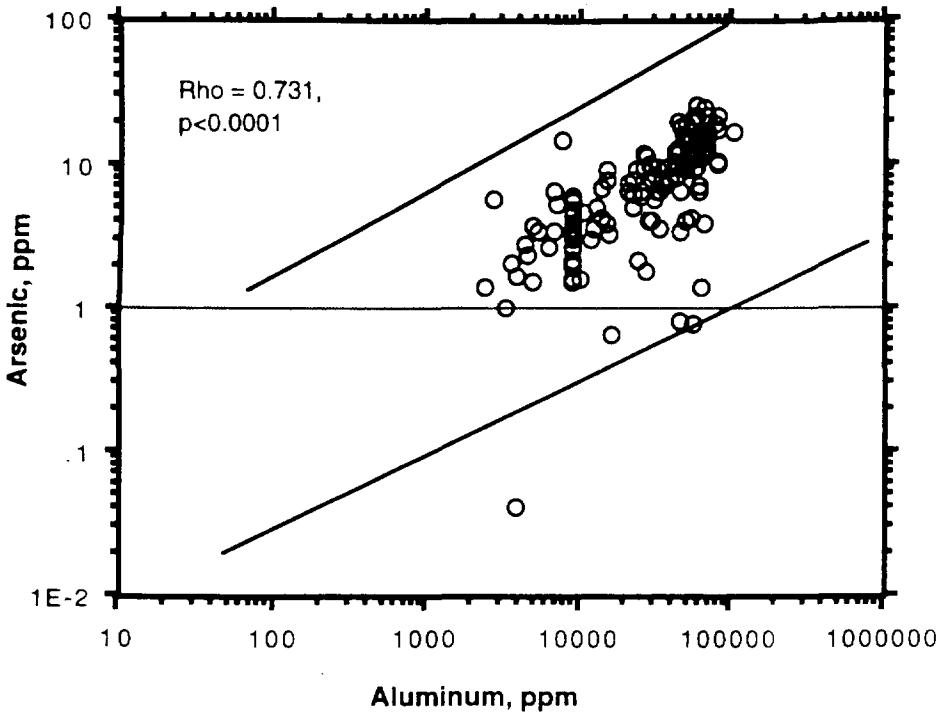


Figure 91. Relationship between the concentrations of aluminum and arsenic in sediment samples from South Carolina/Georgia.

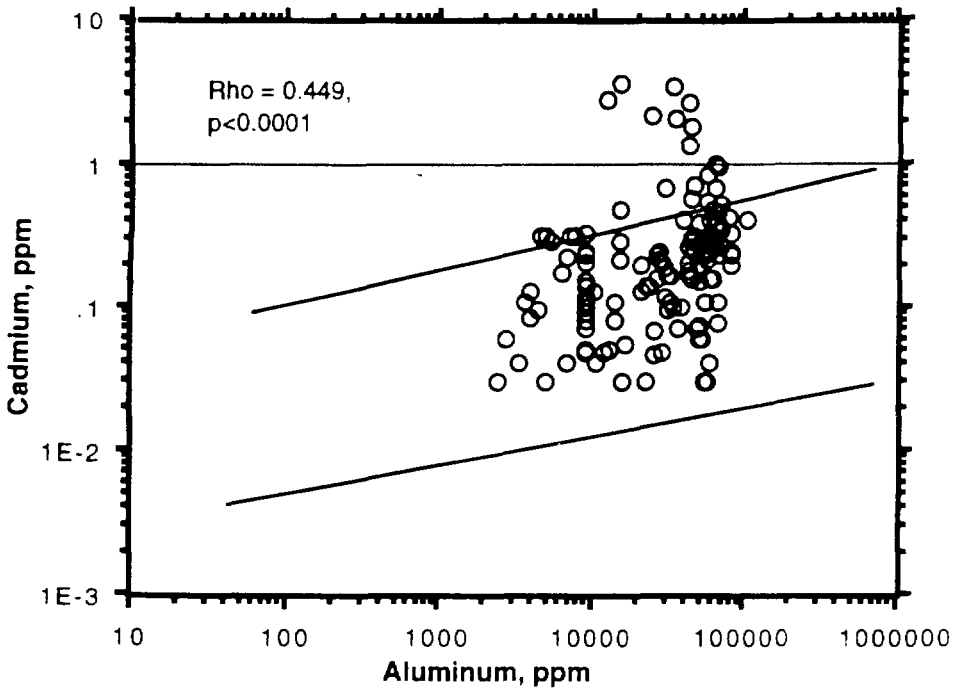


Figure 92. Relationship between the concentrations of aluminum and cadmium in sediment samples from South Carolina/Georgia.

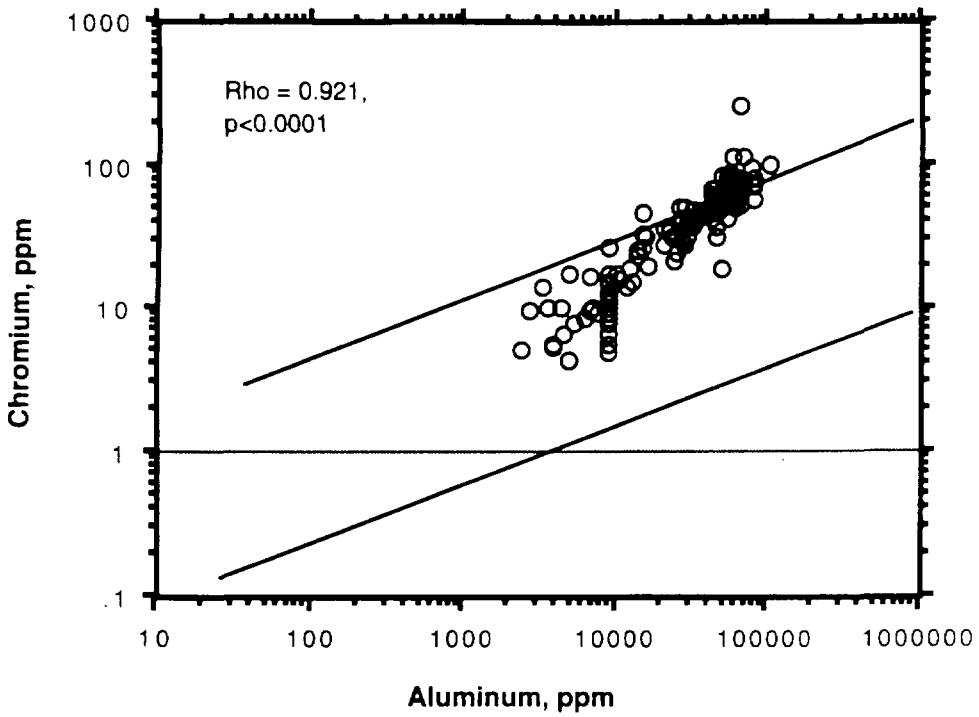


Figure 93. Relationship between the concentrations of aluminum and chromium in sediment samples from South Carolina/Georgia.

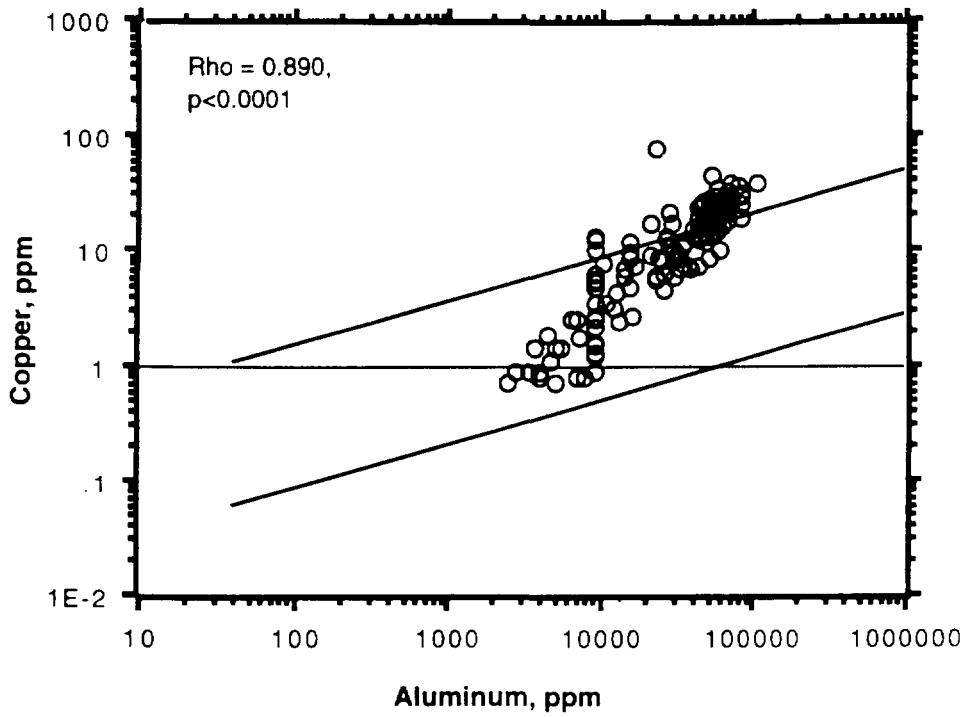


Figure 94. Relationship between the concentrations of aluminum and copper in sediment samples from South Carolina/Georgia.

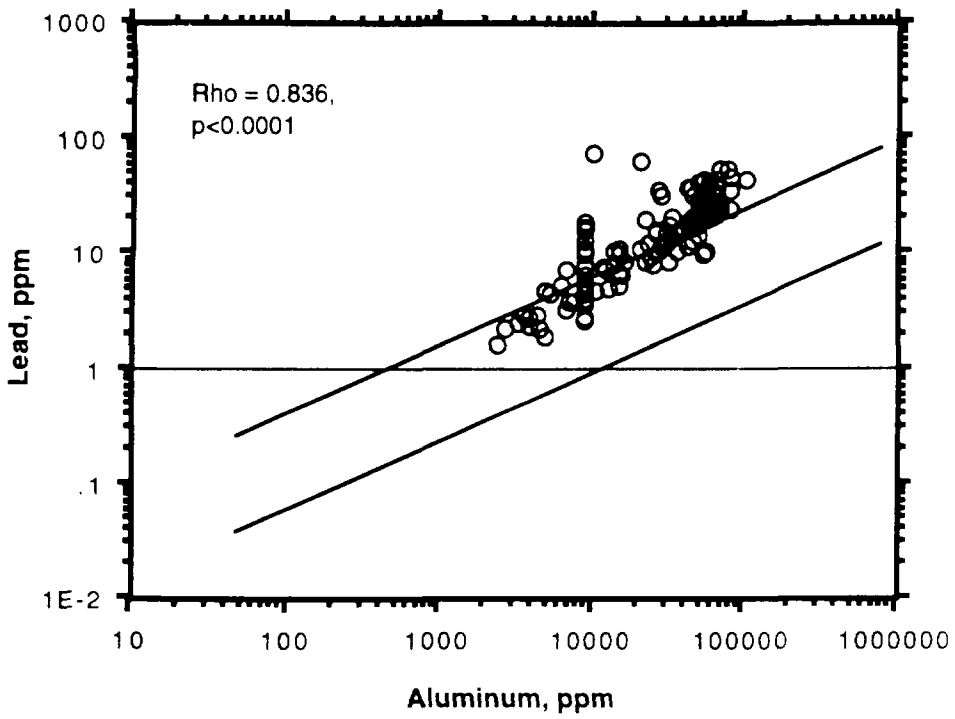


Figure 95. Relationship between the concentrations of aluminum and lead in sediment samples from South Carolina/Georgia.

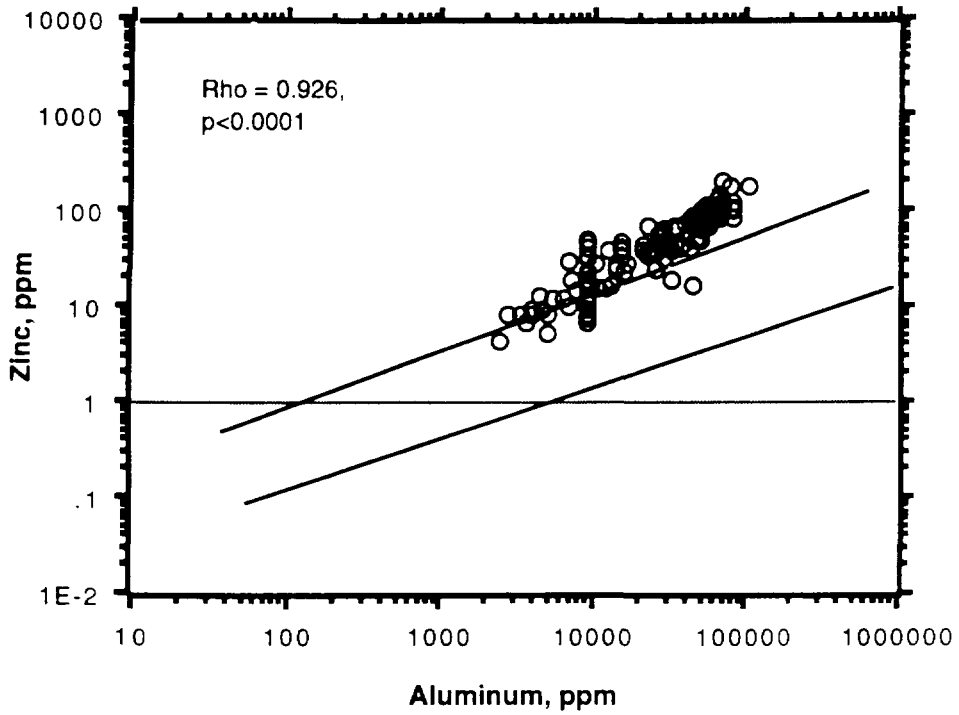


Figure 96. Relationship between the concentrations of aluminum and zinc in sediment samples from South Carolina/Georgia.

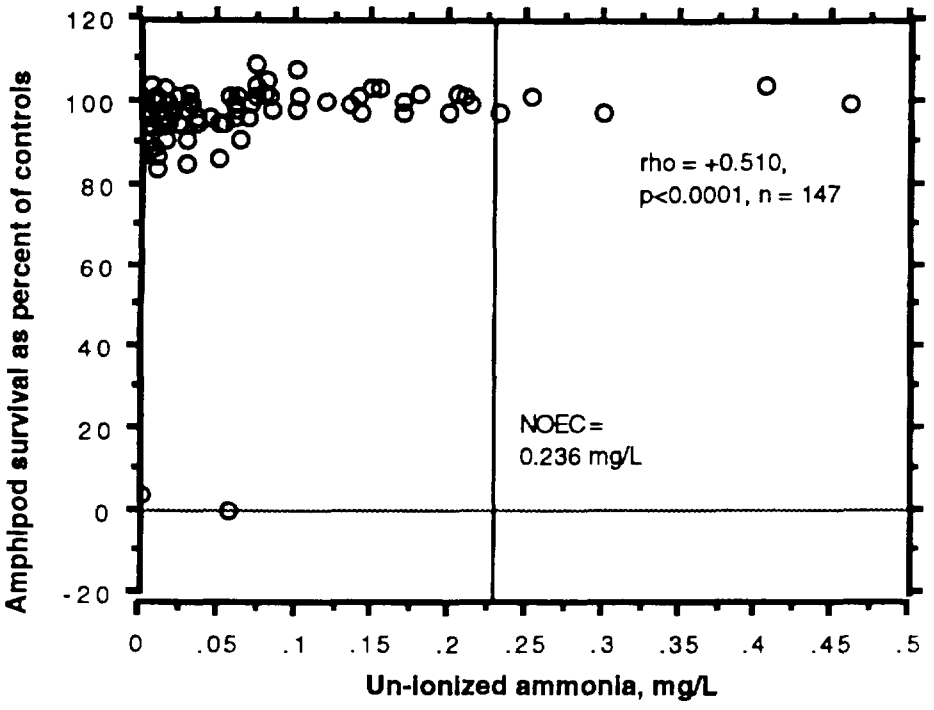


Figure 97. Relationship between the concentrations of un-ionized ammonia in overlying water of test chambers and amphipod survival.

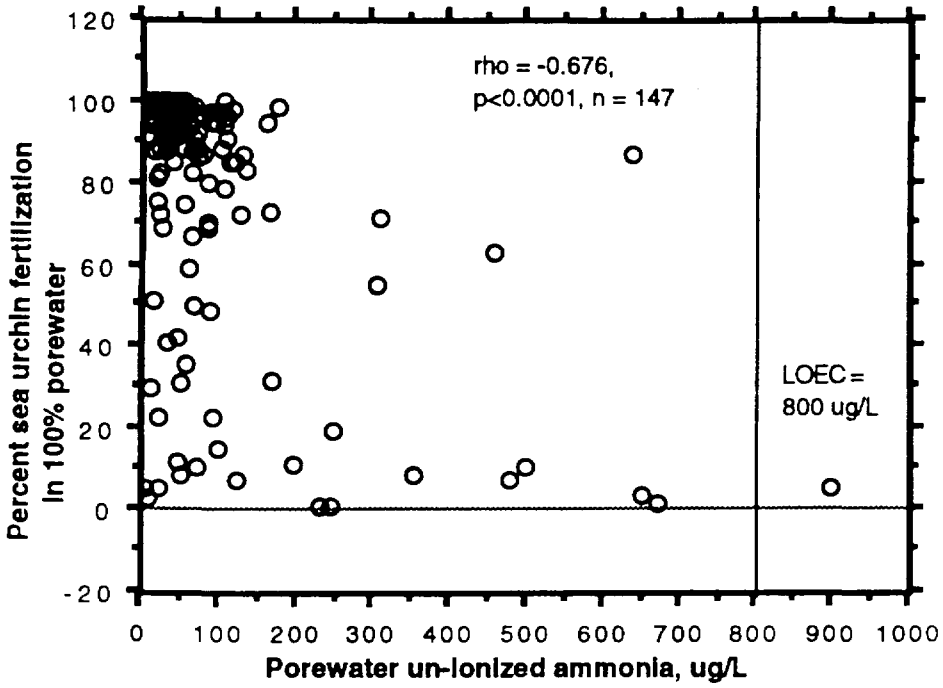


Figure 98. Relationship between un-ionized ammonia in porewater and percent sea urchin fertilization in 100% porewater.

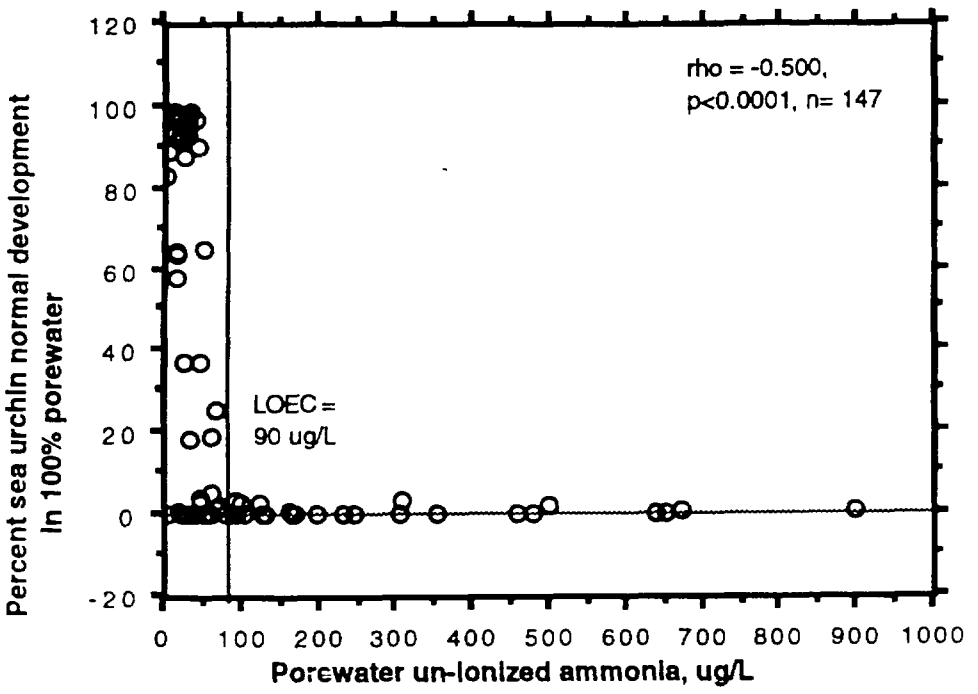


Figure 99. Relationship between the concentrations of un-ionized ammonia in porewater and percent sea urchin normal development in 100% porewater.

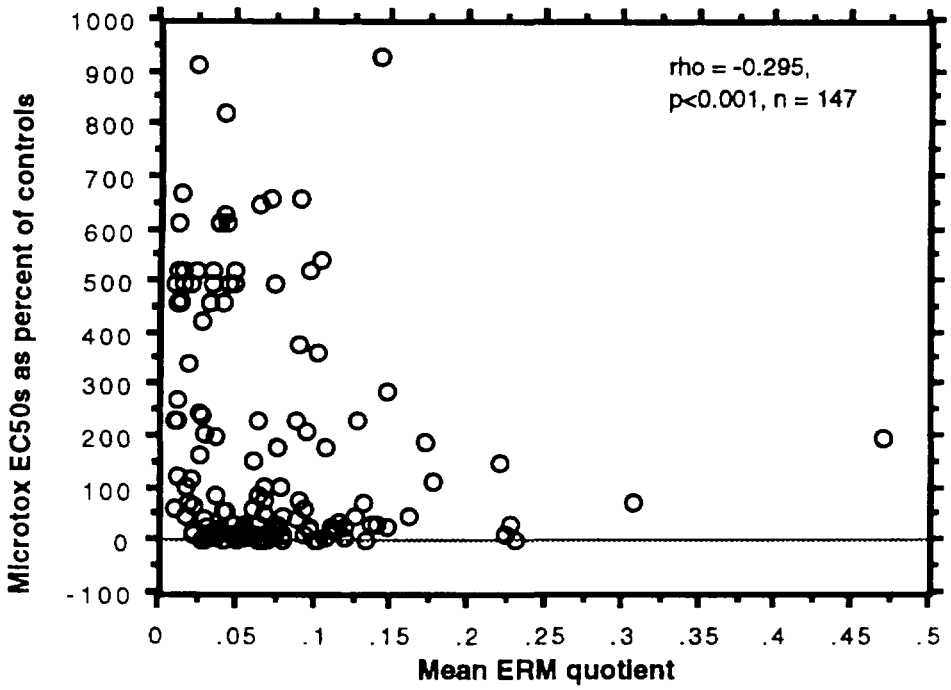


Figure 100. Relationship between mean ERM quotients and microbial bioluminescence.

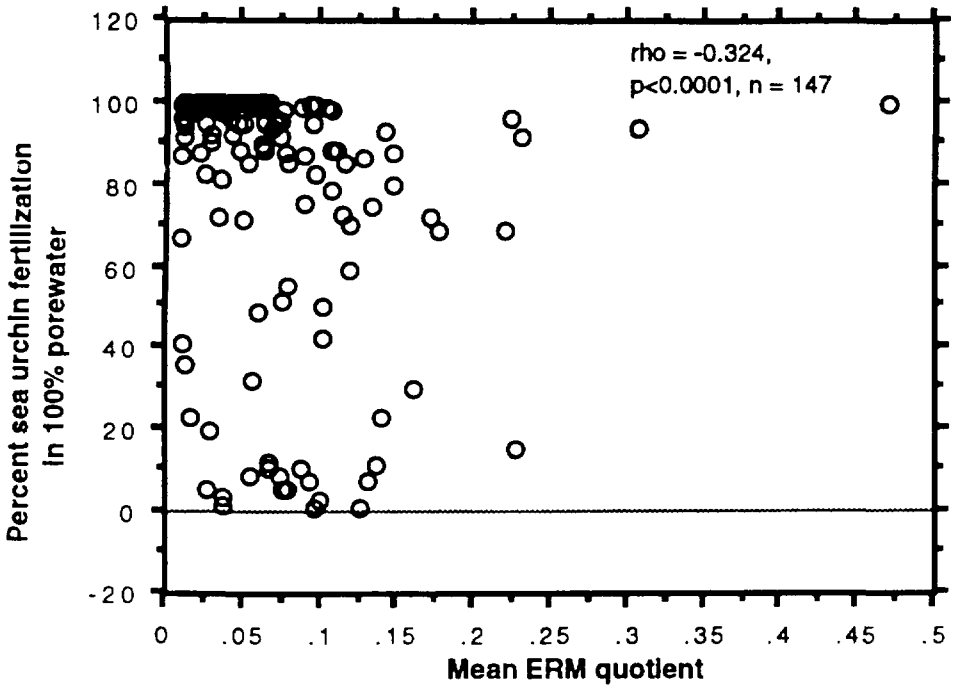


Figure 101. Relationship between mean ERM quotients and percent sea urchin fertilization in 100% porewater.

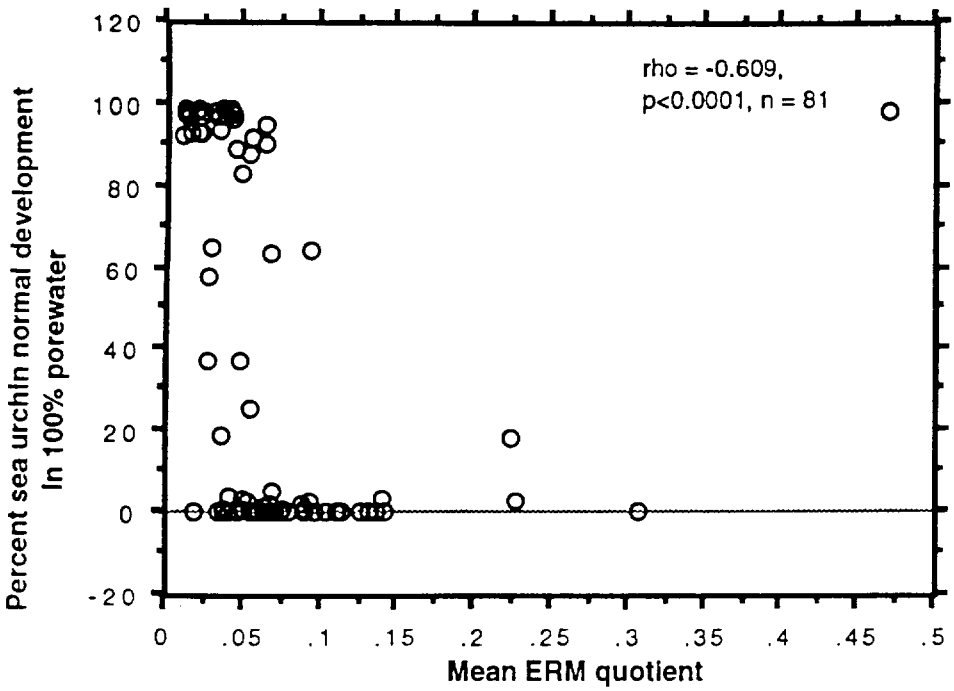


Figure 102. Relationship between mean ERM quotients for 25 substances and percent sea urchin normal development.

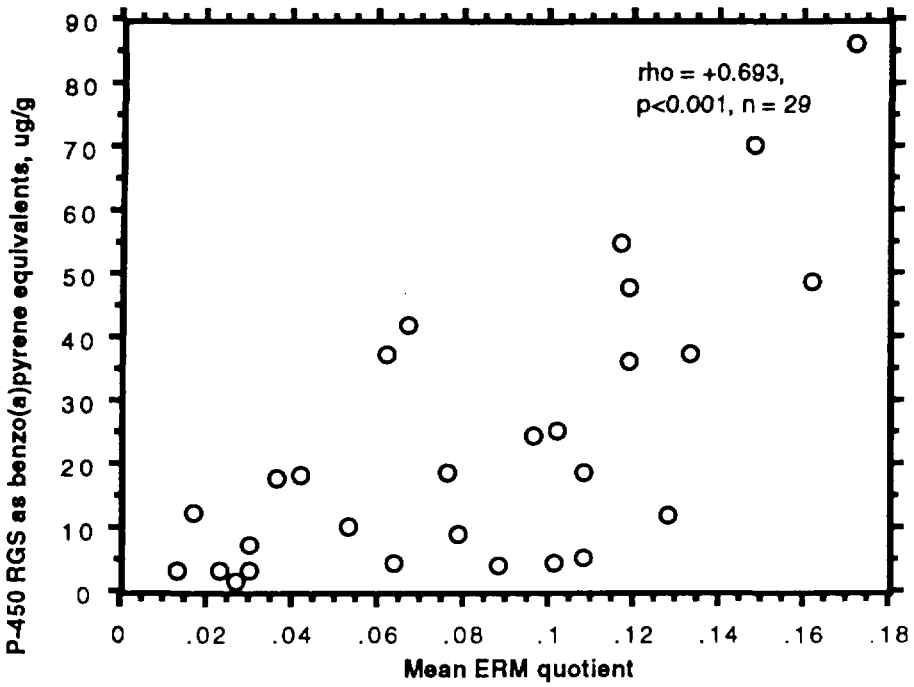


Figure 103. Relationship between mean ERM quotients and cytochrom P450 RGS assay results (as benzo(a)pyrene equivalents).

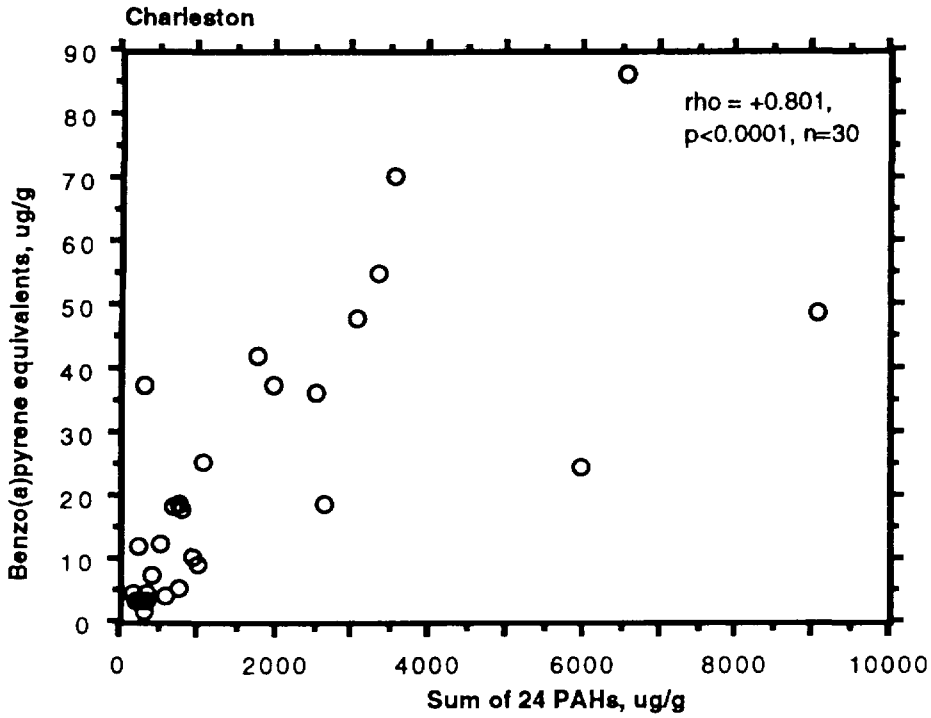


Figure 104. Relationship between the concentrations of total PAHs and cytochrome P-450 RGS bioassay responses.

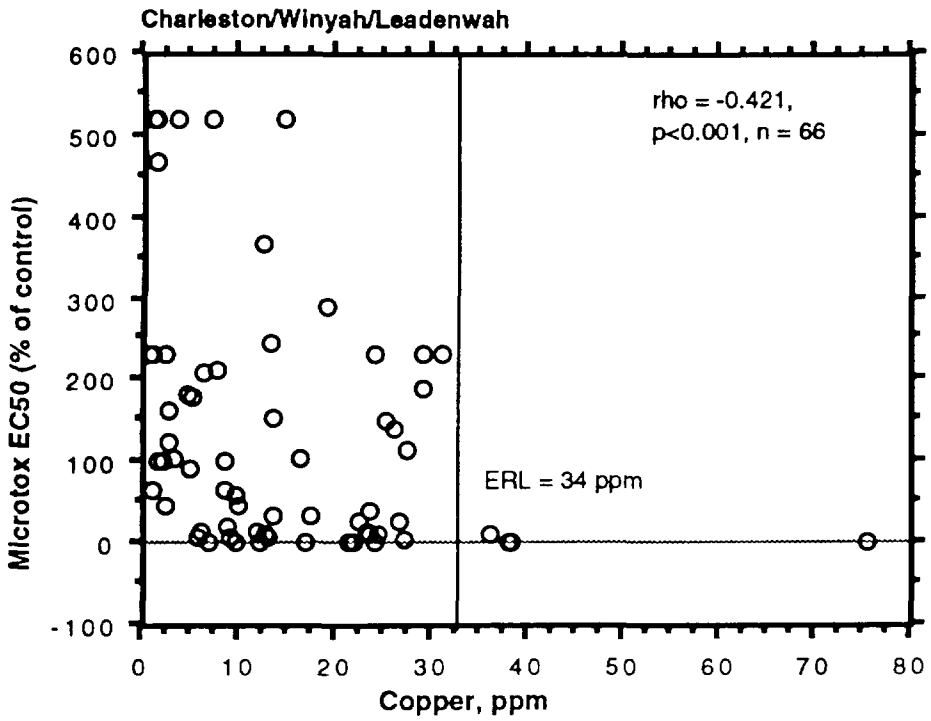


Figure 105. Relationship between microbial bioluminescence and the concentrations of copper in sediments from Charleston Harbor, Winyah Bay, and Leadenwah Creek.

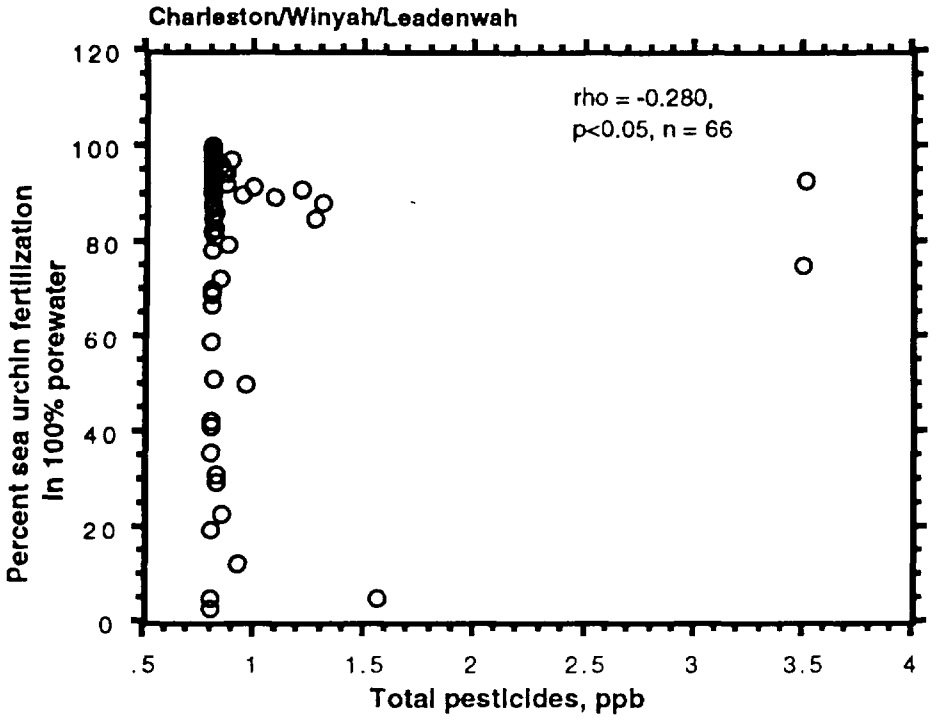


Figure 106. Relationship between sea urchin fertilization and the concentrations of total pesticides in sediments from Charleston Harbor, Winyah Bay, and Leadenwah Creek.

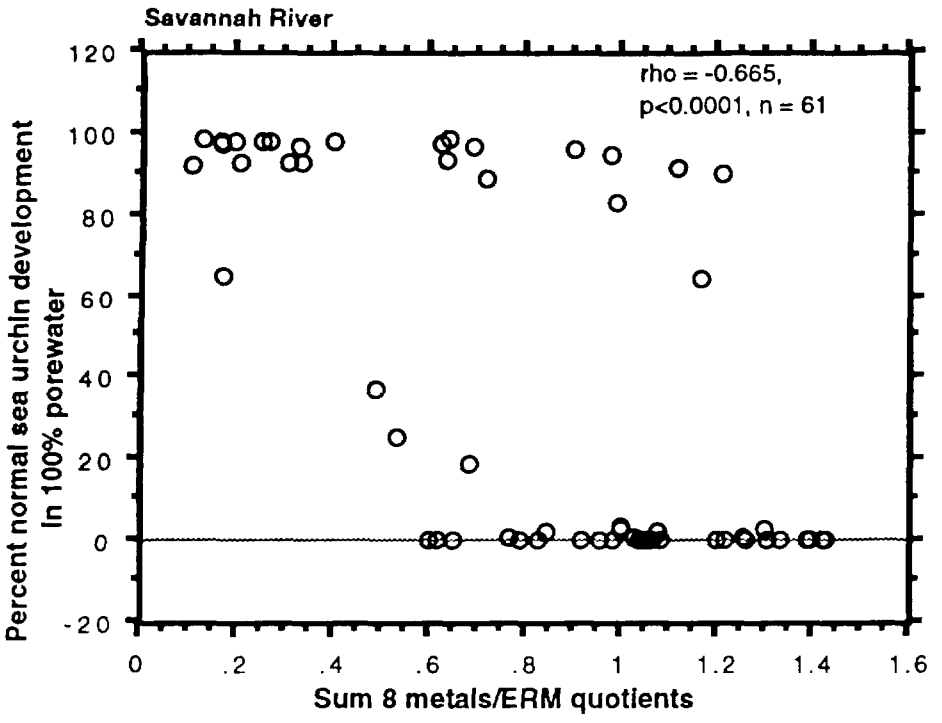


Figure 107. Relationship between the sum of 8 metals/ERM quotients and percent normal sea urchin development in sediments from Savannah River.

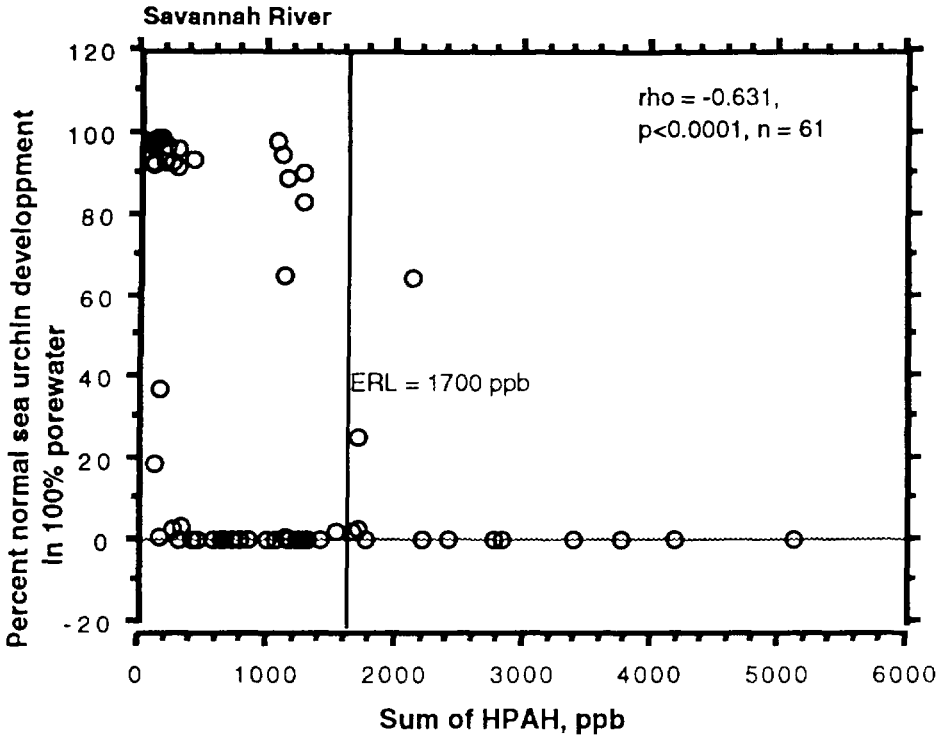


Figure 108. Relationship between percent normal sea urchin development and the sum of total HPAHs in sediments from the Savannah River.

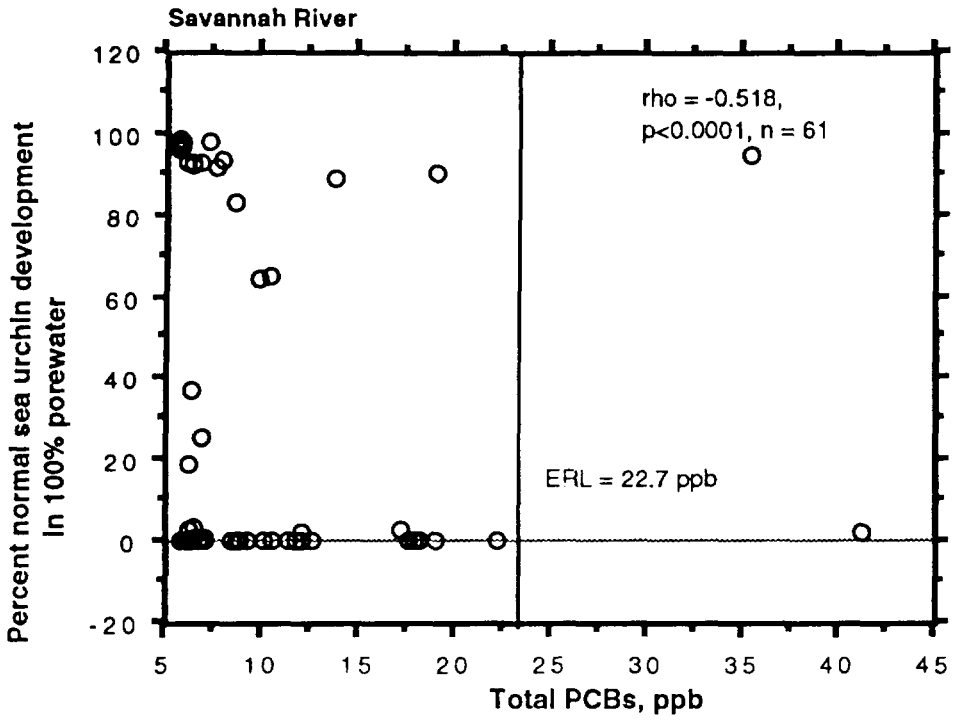


Figure 109. Relationship between percent normal sea urchin development and concentrations of total PCBs in sediments from the Savannah River.

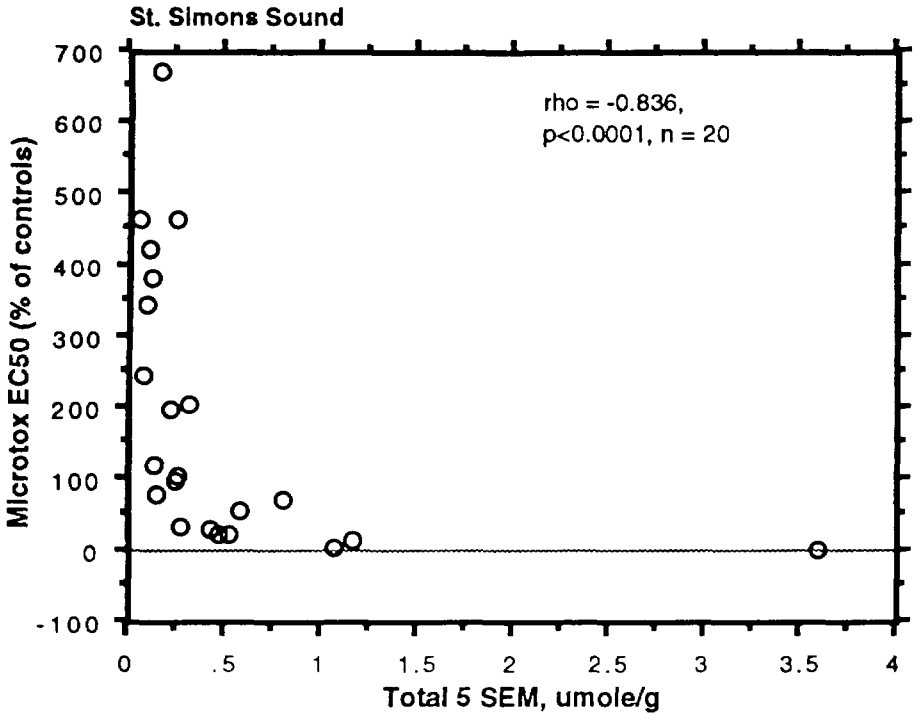


Figure 110. Relationship between microbial bioluminescence and the sums of five simultaneously-extracted metals (SEM) in sediments from St. Simons Sound.

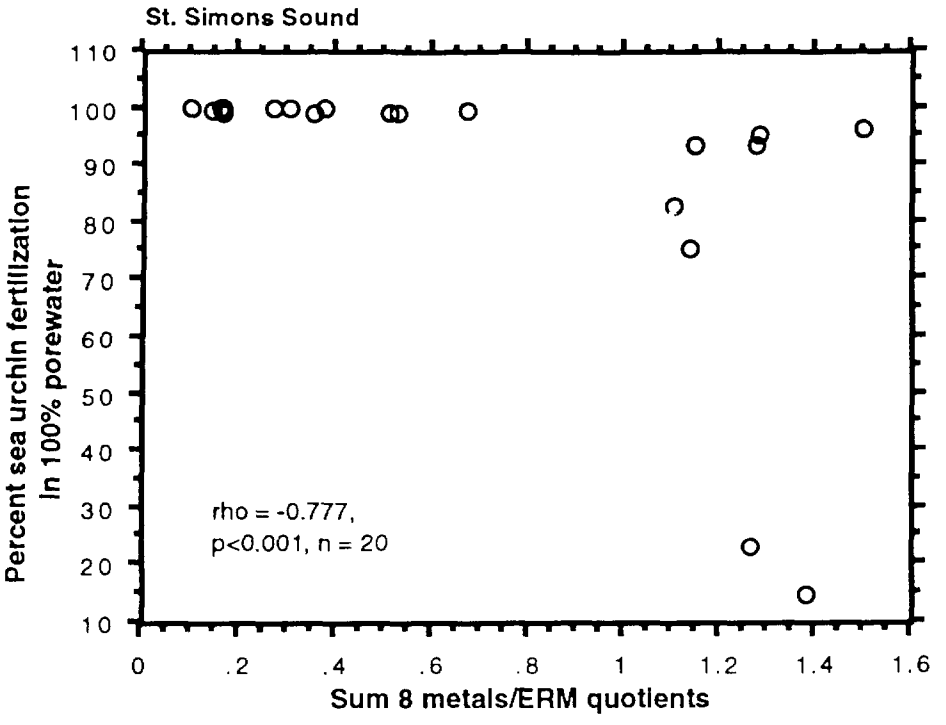


Figure 111. Relationship between percent sea urchin fertilization and the sum of 8 metals/ERM quotients in sediments from St. Simons Sound.

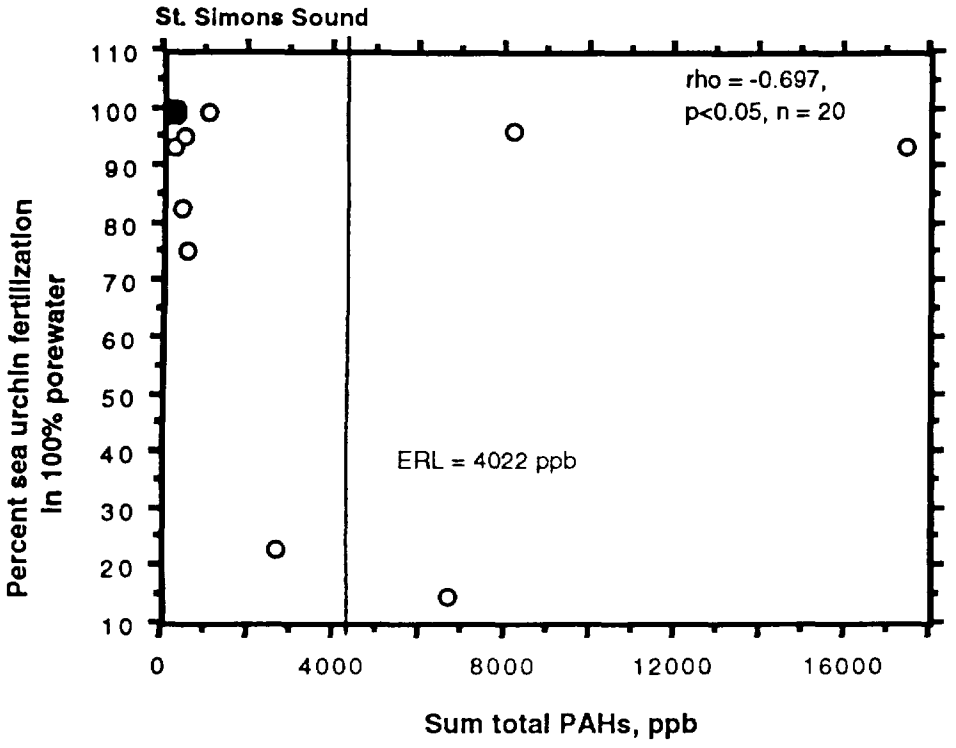


Figure 112. Relationship between sea urchin fertilization and the concentrations of total PAHs in sediments from St. Simons Sound.

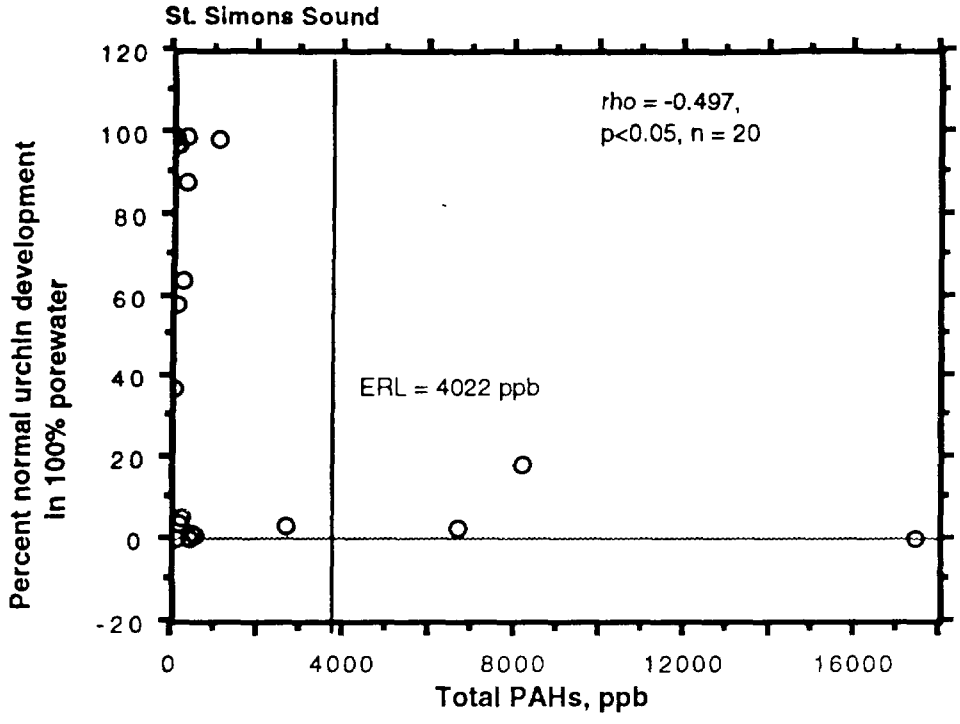


Figure 113. Relationship between normal sea urchin development and the concentrations of total PAHs in sediments from St. Simons Sound.

APPENDIX A1. Field notes from Charleston Harbor and vicinity.		
Strata No.	Station No.	Station Location
A-1	1	upper Leadenwah-Eastern Branch
A-1	2	upper Leadenwah-Eastern Branch
A-1	8	upper Leadenwah Creek off Maybank Highway by Treatment site)
A-2	1	Leadenwah Creek, Middle Creek upper tidal zone below Spartina
A-2	3	Eastern Leadenwah Creek-middle
A-2	7	junction of Eastern and Mid Branch Leadenwah Creek
A-3	1	lower Leadenwah by Eastern Bank
A-3	2	lower Leadenwah Creek
A-3	3	lower Leadenwah-Main Creek by community dock
B-1	1	Winyah Bay; downstream of Steel Mill, upper Georgetown Harbor
B-1	2	Winyah Bay; upper Georgetown Harbor off Front Street by Steel Mill
B-1	3	Winyah Bay; upper Georgetown Harbor below Steel Mill
B-2	1	Winyah Bay; upper Channel beside Paper Mill
B-3	1	Winyah Bay; Turning Basin, downstream from paper mill
B-4	1	Winyah Bay; Sampit Point Channel below Paper Mill and Steel Mill
B-5	1	SE of Marina in Winyah Bay
B-6	1	Winyah Bay; Upper Rabbit Island Channel below Paper Mill)
B6	2	Upper Rabbit Isle Channel-Winyah Bay
B-7	1	Lower Rabbit Isle Channel-Winyah Bay
C-1	1	Charleston Harbor (Off Mt. Pleasant near sea buoy)
C-2	1	Charleston Harbor (Off Ft. Sumter)
C-2	3	Charleston Harbor
C-2	4	Charleston Harbor (west of Ft. Sumter at third range antenna)
C-3	1	Charleston Harbor (1/4 mile east of Castle Pinkney)
C-4	1	Charleston Harbor (1/2 mile east of Castle Pickney)
C-5	1	Charleston Harbor (Coast Guard Dock Ashley River 100 m. off)
D-1	1	Charleston Harbor (City Marina Ashley River)
D-1	2	Charleston Harbor
D-1	3	Charleston Harbor (West of Highway 17, Ashley River)
D-1	4	Charleston Harbor (East of Highway 17 bridge near Ashley Marina)
D-2	1	Charleston Harbor (Ashley River)
D-2	2	Charleston Harbor (Ashley River)
D-2	3	Charleston Harbor (Ashley River across from The Citadel)
D-3	1	Charleston Harbor (Across Ashley River from Koppers Creosote Plant)
D-3	2	Charleston Harbor (Ashley River)
D-3	3	Charleston Harbor (Ashley River)
D-4	1	Charleston Harbor (Duck Island Reach - Ashley River)
D-4	2	Charleston Harbor (Ashley River, Duck Island Reach)
D-4	4	Charleston Harbor (Ashley River, Duck Island Reach)
E-1	1	Charleston Harbor (1/4 mile SW of Patriots Point)
E-1	2	Charleston Harbor (300 yards south of Patriots Point)
E-1	3	Charleston Harbor (Horseroach Channel SW off Yorktown/Patriots Pt)

Appendix A2. Field notes from the upper Savannah River.		
Strata No.	Station No.	Station Location
(US)A1	1	upper Savannah River
(US)A1	2	upper Savannah River (south bank)
(US)A1	3	upper Savannah River (south bank, Ursla Island)
(US)A2	2	upper Savannah River
(US)A2	3	upper Savannah River (West of Confluence of Steamboat River)
(US)A2	4	upper Savannah River
(US)B1	1	upper Savannah River (Port Wentworth turning basin)
(US)B1	2	upper Savannah River (Port Wentworth channel)
(US)B1	5	upper Savannah River (Port Wentworth channel)
(US)B2	1	upper Savannah River (Whiteball channel)
(US)B2	3	upper Savannah River
(US)B2	4	upper Savannah River (Whiteball channel)
(US)B3	3	upper Savannah River (South of Hutchinson Island, Kings Island Channel)
(US)B3	5	upper Savannah River (South Kings Island channel, mouth of Dundee channel)
(US)B3	6	upper Savannah River (Kings Island channel)
(US)B4	4	upper Savannah River (Marsh Island channel east)
(US)B4	5	upper Savannah River (Marsh Island channel east)
(US)B4	6	upper Savannah River (between Kings and Marsh Islands in front of pulp mill)
(US)B5	1	upper Savannah River (east of suspension bridge)
(US)B5	2	upper Savannah River (N.W. of suspension bridge)
(US)B5	3	upper Savannah River (S.W. of suspension bridge)
(US)B6	1	upper Savannah River (front channel)
(US)B6	2	upper Savannah River (front channel)
(US)B6	3	upper Savannah River (front channel)
(US)B7	1	upper Savannah River (wrecks channel)
(US)B7	2	upper Savannah River (wrecks channel)
(US)B7	3	upper Savannah River (wrecks channel)
(US)B8	1	upper Savannah River (Kings Island turning basin)
(US)B8	2	upper Savannah River (Kings Island turning basin)
(US)B8	3	upper Savannah River (Kings Island turning basin)
(US)B9	1	upper Savannah River (Marsh Island turning basin)
(US)B9	2	upper Savannah River
(US)B9	3	upper Savannah River
(US)F	1	upper Savannah River (Finger canal, mouth of Dundee Canal)
(US)F	2	upper Savannah River (Finger canal, mouth of Dundee Canal)
(US)G	1	upper Savannah River (ocean terminal)
(US)G	2	upper Savannah River
(US)H	1	upper Savannah River (Stevens terminal)
(US)H	2	upper Savannah River (Stevens terminal)

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Station Location	Date	Time	Latitude	Longitude	Depth m
(S)E1	1-1	Savannah River (south channel)	6/25/94	16:15 PM	32°05.34 'N	81°00.80 'W	2.0
(S)E1	2-1	Savannah River (south channel)	6/25/94	17:00 PM	32°04.76 'N	80°59.94 'W	1.6
(S)E1	3-1	Savannah River (south channel)	6/25/94	18:02 PM	32°03.86 'N	80°58.15 'W	3.1
(S)C	1	Back River	6/26/94	11:30 AM	32°05.77 'N	81°04.23 'W	3.6
(S)C	2	Back River	6/26/94	12:15 PM	32°05.39 'N	81°03.59 'W	3.3
(S)C	3	Back River	6/26/94	13:04 PM	32°05.44 'N	81°04.07 'W	2.3
(S)E2	1	Savannah River (south channel)	6/26/94	14:30 PM	32°03.74 'N	80°57.89 'W	0.9
(S)E2	2	Savannah River (south channel)	6/26/94	15:23 PM	32°02.39 'N	80°56.44 'W	4.0
(S)E2	3	Savannah River (south channel)	6/26/94	16:25 PM	32°01.88 'N	80°55.44 'W	3.7
(S)D1	1-1	Savannah River (lower channel)	6/27/94	9:35 PM	32°04.89 'N	81°02.31 'W	8.4
(S)D1	2-2	Savannah River (lower channel)	6/27/94	11:05 PM	32°05.37 'N	81°01.63 'W	6.5
(S)D1	3-1	Savannah River (lower channel)	6/27/94	12:10 PM	32°05.91 'N	81°00.30 'W	2.9
(S)D2	3-1	Savannah River (lower channel)	6/27/94	17:15 PM	32°03.72 'N	80°57.00 'W	4.0
(S)D2	2-2	Savannah River (lower channel)	6/27/94	18:20 PM	32°04.59 'N	80°58.52 'W	5.4
(S)D2	1-1	Savannah River (lower channel)	6/28/94	19:20 PM	32°04.48 'N	80°58.83 'W	3.7
(S)E3	2	Savannah River (south channel)	6/28/94	10:05 AM	32°01.25 'N	80°53.74 'W	3.8
(S)E3	5	Savannah River (south channel)	6/28/94	10:50 AM	32°01.57 'N	80°54.09 'W	4.8
(S)D3	1-4	Savannah River (lower channel)	6/28/94	12:28 PM	32°03.09 'N	80°56.44 'W	2.9
(S)D3	2-1	Savannah River (lower channel)	6/28/94	13:29 PM	32°02.51 'N	80°55.32 'W	2.5
(S)D3	3-2	Savannah River (lower channel)	6/28/94	14:49 PM	32°02.12 'N	80°54.96 'W	3.5
(S)E3	9	Savannah River (south channel)	6/28/94	15:50 PM	32°01.13 'N	80°53.18 'W	4.5

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Air Temp. °C	Surface Temp. °C	Bottom Temp. °C	Surface Salinity ppt	Bottom Salinity ppt
(S)E1	1-1	nd	28.0	28.0	6.5	7.0
(S)E1	2-1	nd	28.0	27.0	8.0	8.5
(S)E1	3-1	nd	28.0	28.5	12.0	14.2
(S)C	1	25.0	27.5	28.0	4.2	8.8
(S)C	2	nd	28.0	28.3	3.9	6.6
(S)C	3	nd	28.5	28.5	5.9	8.7
(S)E2	1	nd	27.8	28.2	12.6	12.3
(S)E2	2	nd	28.5	25.0	14.0	16.0
(S)E2	3	nd	26.0	24.9	15.5	16.1
(S)D1	1-1	26.5	27.9	28.0	5.0	14.0
(S)D1	2-2	27.0	27.5	27.5	8.6	12.3
(S)D1	3-1	27.8	27.9	27.4	11.0	15.0
(S)D2	3-1	26.8	25.5	25.2	11.8	14.0
(S)D2	2-2	22.5	27.0	27.5	8.5	10.7
(S)D2	1-1	nd	26.0	25.1	7.3	7.6
(S)E3	2	22.0	23.0	23.2	19.8	24.3
(S)E3	5	nd	23.5	26.9	21.1	22.2
(S)D3	1-4	nd	27.0	27.4	23.9	25.1
(S)D3	2-1	nd	27.8	27.5	22.5	25.4
(S)D3	3-2	27.5	28.0	27.5	26.0	26.0
(S)E3	9	26.5	27.5	27.5	16.5	16.5

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Surface D.O. mg/L	Bottom D.O. mg/L	Surface Conductivity micro moles	Bottom Conductivity micro moles
(S)E1	1-1	4.6	4.6	12,000	12,500
(S)E1	2-1	4.7	4.8	14,100	15,100
(S)E1	3-1	5.3	6.5	25,000	21,100
(S)C	1	5.1	3.5	7,900	6,100
(S)C	2	5.5	3.9	7,300	11,900
(S)C	3	4.8	3.75	10,800	15,900
(S)E2	1	5.1	5 1	21,800	21,600
(S)E2	2	5.3	4.85	24,500	26,200
(S)E2	3	5.3	5.1	25800	25800
(S)D1	1-1	4.5	3.8	8,400	25,000
(S)D1	2-2	4.9	4.6	15,400	21,880
(S)D1	3-1	4.8	4.7	19,000	26,000
(S)D2	3-1	5.4	5.2	19,200	23,300
(S)D2	2-2	5.0	4.5	15,300	18,500
(S)D2	1-1	4.7	4.85	12,500	13,000
(S)E3	2	6.2	5.6	30,500	37,000
(S)E3	5	5.9	5.5	32,700	36,500
(S)D3	1-4	5.5	5.5	49,700	42,000
(S)D3	2-1	6.1	5.4	38,200	42,300
(S)D3	3-2	6.15	6.4	43,500	43,500
(S)E3	9	6.45	6.5	28,500	29,000

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Sediment Description
(S)E1	1-1	2 cm dark brown muddy sand over black clay, slight petroleum sheen.
(S)E1	2-1	2 cm brown muddy sand overlying black clay layer.
(S)E1	3-1	1st grab: muddy sand, shell debris; 2nd grab: sandy grey clay marl, lots of clay, mud crab; note: it took 6 grabs to get sample.
(S)C	1	1/2 cm thin brown film over black silty clay, "silty mud", slight H2S odor; note: sampling site is next to spoil island.
(S)C	2	1/2 cm light brown silty clay overlying black silty clay; note about sampling site: anchorage area, barges, impounded waters, dam; photos: roll E: 1-3.
(S)C	3	Light brown medium to course sand; spoil area adjacent; boat anchorage; channel runs 45 ft. deep with "shoulders" starting approximately 15 ft.; photos: roll E: 4-6.
(S)E2	1	Brown muddy sand, medium-course grain size, polychaete tubes, shell debris, spartina both sides, south of Bird Island; photos: roll E: 7-8.
(S)E2	2	2 mm light brown sandy clay over grey clay (curling up the sides of grab), Highway 80 nearby, spartina both banks; photos: roll E: 9-10.
(S)E2	3	1 cm light brown sandy clay with some shell debris over black sandy clay, no odor, spartina marsh on both sides, Highway 80 to the south; photos: roll E: 12-13.
(S)D1	1-1	2 cm soft olivine silt over black silty clay with some gravel, slight petroleum sheen; 3rd grab: sandy clay over black; 4th grab: same as 3rd; station at confluence of Back River and Savannah River, ship traffic, petroleum factory, spartina marsh to the south, it took 9 drops to get sample; photos: roll E: 14-20.
(S)D1	2-2	Thin layer of brown coarse sand (sand appears to be in furrows) over firm grey clay marl, spoil island to northwest, refinery to south; photos: roll E: 24-26.
(S)D1	3-1	Light brown-olivine soft sandy-silty clay, petroleum sheen, gravel in grab, spoil islands on both sides, note: station moved closer to shoreline, have to get river stations on slack tides, Elba Island is a spoil island; photos: roll F: 1-3.
(S)D2	3-1	Brown muddy sand wi some clay, shell hash, clam (mulinia); 2nd grab: more clay, forrest/ marsh on both banks, S+E of Intracoastal; photos: roll F: 4-6.
(S)D2	2-2	1 mm brown sand layer over grey clay, some shell hash; 2nd grab: 5 mm brown sand over grey clay; 3rd grab: 4-5 mm sand over grey clay; went to station 2-2 because slope of channel was too steep; photos: roll F: 7-10.

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Sediment Description
(S)D2	1-1	Grey clay marl on surface, thin layer brown sand over grey clay; 2nd grab: marl/slate; numerous drops - moved station from 45' to 15' along shore; photos: roll F: 12-13.
(S)E3	2	Brown sand with some clay, silt mixed in with sand, shell hash; 2nd grab: more sand component with clay inclusions; spartina both sides; bridge to west; photos: roll F: 14-18.
(S)E3	5	Olivine/brown silt > 1 mm over dark charcoal clay (pluff mud), shell hash on top, some wood chips, fecal pellets on surface, worm tubes, polychaete burrows; spartina on both sides, bridge to east; photos: roll F: 19-21.
(S)D3	1-4	2 mm brown silt over sand, highly bedded, clay inclusions, worms poly or oligochaetes; 1-1: shells, coarse gravel, coarse sand - rejected; 1-2: same; 1-3: same local; photos: roll F: 22-24.
(S)D3	2-1	Thin brown silt layer over coarse sand, shell and rock with clay inclusions below "muddy sand", vegetation on both banks, sheen/specks visible when homogenizing; photos: roll G: 5-8.
(S)D3	3-2	Thin brown silt over dark charcoal silt, no noticable odor, some plant debris, gray clay inclusions, worm tubes and hogchoker observed, vegetation on both banks; 3-1: dredged - rock only; photos: roll G: 9-13.
(S)E3	9	Pluff mud with thin brown silt layer on top, some worm tubes, some plant material, lots of biological activity, vegetation on both banks; photos: roll G: 15-19.

Appendix A3. Field notes from the lower Savannah River.

Strata No.	Station No.	Station Location	Date	Time	Latitude	Longitude	Depth m
(S)E1	1-1	Savannah River (south channel)	6/25/94	16:15 PM	32°05.34 'N	81°00.80 'W	2.0
(S)E1	2-1	Savannah River (south channel)	6/25/94	17:00 PM	32°04.76 'N	80°59.94 'W	1.6
(S)E1	3-1	Savannah River (south channel)	6/25/94	18:02 PM	32°03.86 'N	80°58.15 'W	3.1
(S)C	1	Back River	6/26/94	11:30 AM	32°05.77 'N	81°04.23 'W	3.6
(S)C	2	Back River	6/26/94	12:15 PM	32°05.39 'N	81°03.59 'W	3.3
(S)C	3	Back River	6/26/94	13:04 PM	32°05.44 'N	81°04.07 'W	2.3
(S)E2	1	Savannah River (south channel)	6/26/94	14:30 PM	32°03.74 'N	80°57.89 'W	0.9
(S)E2	2	Savannah River (south channel)	6/26/94	15:23 PM	32°02.39 'N	80°56.44 'W	4.0
(S)E2	3	Savannah River (south channel)	6/26/94	16:25 PM	32°01.88 'N	80°55.44 'W	3.7
(S)D1	1-1	Savannah River (lower channel)	6/27/94	9:35 PM	32°04.89 'N	81°02.31 'W	8.4
(S)D1	2-2	Savannah River (lower channel)	6/27/94	11:05 PM	32°05.37 'N	81°01.63 'W	6.5
(S)D1	3-1	Savannah River (lower channel)	6/27/94	12:10 PM	32°05.91 'N	81°00.30 'W	2.9
(S)D2	3-1	Savannah River (lower channel)	6/27/94	17:15 PM	32°03.72 'N	80°57.00 'W	4.0
(S)D2	2-2	Savannah River (lower channel)	6/27/94	18:20 PM	32°04.59 'N	80°58.52 'W	5.4
(S)D2	1-1	Savannah River (lower channel)	6/28/94	19:20 PM	32°04.48 'N	80°58.83 'W	3.7
(S)E3	2	Savannah River (south channel)	6/28/94	10:05 AM	32°01.25 'N	80°53.74 'W	3.8
(S)E3	5	Savannah River (south channel)	6/28/94	10:50 AM	32°01.57 'N	80°54.09 'W	4.8
(S)D3	1-4	Savannah River (lower channel)	6/28/94	12:28 PM	32°03.09 'N	80°56.44 'W	2.9
(S)D3	2-1	Savannah River (lower channel)	6/28/94	13:29 PM	32°02.51 'N	80°55.32 'W	2.5
(S)D3	3-2	Savannah River (lower channel)	6/28/94	14:49 PM	32°02.12 'N	80°54.96 'W	3.5
(S)E3	9	Savannah River (south channel)	6/28/94	15:50 PM	32°01.13 'N	80°53.18 'W	4.5

APPENDIX A4. Field notes from St. Simons Sound.

Strata No.	Station No.	Station Location	Date	Time	Latitude	Longitude	Depth m
(B)A1	1	Turtle River	6/22/94	9:11 AM	31°13.08 'N	81°33.64 'W	8.5
(B)A2	2	Turtle River	6/22/94	10:41 AM	31°12.00 'N	81°33.26 'W	5.0
(B)A3	1	Turtle River	6/22/94	11:46 AM	31°11.66 'N	81°32.21 'W	3.0
(B)P	1	Purvis Creek	6/22/94	12:40 PM	31°11.19 'N	81°31.02 'W	7.0
(B)D1	1	Turtle River	6/22/94	15:38 PM	31°10.25 'N	81°31.60 'W	7.5
(B)D2	1	Turtle River	6/22/94	16:34 PM	31°08.90 'N	81°31.87 'W	6.2
(B)E2	2	St. Simons Sound	6/23/94	8:40 AM	31°05.76 'N	81°26.66 'W	7.0
(B)E1	1	St. Simons Sound	6/23/94	9:30 AM	31°06.83 'N	81°29.41 'W	3.5
(B)D3	2	Turtle River	6/23/94	11:10 AM	31°07.08 'N	81°30.25 'W	3.5
(B)B1	1	Academy Creek	6/23/94	12:30 PM	31°09.48 'N	81°29.97 'W	5.0
(B)B2	1	Academy Creek	6/23/94	13:05 PM	31°09.14 'N	81°29.98 'W	4.5
(B)C1	1	East River	6/23/94	13:47 PM	31°08.83 'N	81°29.94 'W	8.5
(B)C2	1	East River	6/23/94	14:26 PM	31°07.90 'N	81°29.69 'W	6.5
(B)C3	1	East River	6/23/94	15:27 PM	31°07.81 'N	81°29.66 'W	8.0
(B)E3	1	St. Simons Sound	6/24/94	9:00 AM	31°06.97 'N	81°25.80 'W	3.0
(B)G3	1	St. Simons Sound	6/24/94	9:55 AM	31°08.11 'N	81°25.18 'W	6.8
(B)G2	1	St. Simons Sound	6/24/94	11:10 AM	31°08.11 'N	81°25.18 'W	5.1
(B)G1	1	Back River	6/24/94	12:10 PM	31°08.96 'N	81°26.66 'W	6.5
(B)F	1-1	Terry Creek	6/24/94	13:00 PM	31°09.90 'N	81°27.64 'W	3.5
(B)F	2-1	Dupree Creek	6/24/94	13:40 PM	31°09.96 'N	81°28.28 'W	1.1

Appendix B1. Toxicity and chemistry data from Charleston Harbor, Leadenwah Creek. and Winyah Bay.					
NMFS Lab. No.	STATION No.	Location	Percent amph-ipod survival	Amph Survival as percent of control	Significance
93-146	C1-1	Ashley River	86	101.18	ns
93-147	C2-4	Ashley River	84	98.82	ns
93-148	C3-1	Ashley River	86	101.18	ns
93-149	C4-1	Ashley River	93	109.41	ns
93-150	CHP4	Plum Isl. Outfall	83	97.65	ns
93-151	C5-1	Ashley River	87	102.35	ns
93-152	D1-1	Ashley River	91	107.06	ns
93-153	A2-3	Leadenwah Creek	87	102.35	ns
93-154	A3-1	Leadenwah Creek	86	101.18	ns
93-155	A3-3	Leadenwah Creek	86	101.18	ns
93-156	A2-7	Leadenwah Creek	88	103.53	ns
93-157	A2-1	Leadenwah Creek	87	102.35	ns
93-158	A1-1	Leadenwah Creek	90	105.88	ns
93-159	A1-2	Leadenwah Creek	91	107.06	ns
93-160	CHP5	Brittle Bank Park	85	100.00	ns
93-161	CHP8	Brickyard Creek	87	102.35	ns
93-162	D4-1	Ashley River	84	98.82	ns
93-163	D4-2	Ashley River	89	104.71	ns
93-164	D4-4	Ashley River	87	102.35	ns
93-165	D2-1	Ashley River	88	103.53	ns
93-166	D2-3	Ashley River	77	90.59	ns
93-167	D2-2	Ashley River	90	105.88	ns
93-168	CHP6	Koppers Creosote	82	96.47	ns
93-169	D3-3	Ashley River	88	103.53	ns
93-170	D3-1	Ashley River	81	95.29	ns
93-171	CHP7	Dolphin Cv Marina	85	100.00	ns
93-172	D3-2	Ashley River	91	107.06	ns
93-173	E1-1	Cooper River	81	95.29	ns
93-174	E2-2	Cooper River	84	98.82	ns
93-175	E2-1	Cooper River	85	100.00	ns
93-176	A1-8	Leadenwah Creek	82	96.47	ns
93-177	Inlet.	North Inlet	90	105.88	ns
93-178	D1-3	Ashley River	85	100.00	ns
93-179	D1-4	Ashley River	79	92.94	ns
93-180	CHP3	Aquarium Site	84	98.82	ns
93-181	E1-3	Cooper River	90	105.88	ns
93-182	E1-2	Cooper River	85	100.00	ns
93-183	E3-1	Cooper River	90	105.88	ns
93-184	E3-3	Cooper River	81	95.29	ns
93-185	CHP2	Romney St. Landfill	90	105.88	ns
93-186	A3-2	Leadenwah Creek	87	102.35	ns
93-196	H4-2	Cooper River	91	103.41	ns
93-197	H4-3	Cooper River	91	103.41	ns
93-198	H4-5	Cooper River	94	106.82	ns
93-199	H5-2	Cooper River	93	105.68	ns

Appendix B2. Toxicity and chemistry data from upper and lower Savannah River sediments.

MSL Lab. Id. No.	STATION Number	Location	% Amph surv.	Amph Surv as % of control	Signif.	Microtox Ave % of samples
94-216	Ref. No. Inlet					11.28816667
94-217	E1,2-1	South Channel	93	100	ns	7.758366667
94-218	E1,3-1	South Channel	93	100	ns	67.66666667
94-219	E1-1	South Channel	93	100	ns	4.8972
94-220	C1	Back River	85	91	@	0.979766667
94-221	E2-2	South Channel	95	102	ns	51
94-222	E2-3	South Channel	92	99	ns	3.742533333
94-223	E2-1	South Channel	87	94	ns	69.30493333
94-224	C3	Back River	90	97	ns	67.66666667
94-225	C2	Back River	85	91	ns	1.05543333
94-226	D1,1-1	Lower Channel	85	91	ns	1.192733333
94-227	D1,2-2	Lower Channel	94	101	ns	67.66666667
94-228	D1,3-1	Lower Channel	90	97	ns	1.1924
94-229	D2,1-1	Lower Channel	89	94	ns	67.66666667
94-230	D2,2-2	Lower Channel	91	96	ns	101
94-231	D2,3-1	Lower Channel	83	87	ns	8.0994
94-242	Ref. No. Inlet					10.7696
94-243	E3-2	South Channel	89	94	ns	3.068633333
94-244	E3-5	South Channel	90	95	ns	0.084266667
94-245	D3,1-4	Lower Channel	84	88	@	51
94-246	D3,2-1	Lower Channel	95	100	ns	30.13476667
94-247	D3,3-2	Lower Channel	91	96	ns	2.1175
94-248	E3-9	South Channel	91	96	ns	1.616433333
94-266	B5-1	City Channel	96	102	ns	66.74363333
94-267	B5-2	City Channel	98	104	ns	95.094
94-268	G1	Ocean Terminal	91	97	ns	2.079633333
94-269	G2	Ocean Terminal	96	102	ns	7.769366667
94-270	H1	Steven Terminal	97	103	ns	3.181533333
94-271	H2	Steven Terminal	92	98	ns	2.7673
94-272	H3	Steven Terminal				2.507133333
94-273	Ref. No. Inlet					10.261333
94-274	B9-1	City Channel	94	100	ns	1.451233333

Appendix I Toxicity and chemistry data from St. Simons Sound.

MSL Lab Id No.	STATION No.	Location	% Amph surv.	Amph Surv as % of control	Signif.	Microtox EC50 % of samples	Microtox EC50 (mg/ml)	Microtox EC50 %ctl. (216 & 242)	Signif.
94-191	A1 -1	upper Turtle R.	89	95	ns	37.79	1.83	342.64	ns
94-192	A2 -2	upper Turtle R.	90	96	ns	51	3.70	462.422	ns
94-193	A3 -1	upper Turtle R.	89	95	ns	8.55	0.63	77.4844	ns
94-194	D1 -1	Blythe Isl. Range	92	98	ns	46.71	3.45	423.484	ns
94-195	D2 -1	Blythe Isl. Range	92	98	ns	26.76	2.00	242.607	ns
94-196	P1	Purvis Cr.	92	98	ns	21.49	1.61	194.889	ns
94-197	B2 -1	Academy Cr.	94	100	ns	7.8791	0.58	71.4406	ns
94-198	C1 -1	East River Harbor	95	101	ns	3.3155	0.25	30.062	ns
94-199	B1 -1	Academy Cr.	92	98	ns	3.6969	0.28	33.5202	ns
94-200	C3-1	East River Harbor	95	101	ns	42	3.27	380.86	ns
94-201	C2 -1	East River Harbor	99	105	ns	2.43	0.17	22.0315	**
94-202	D3 -2	Blythe Isl. Range	90	96	ns	51	3.80	462.422	ns
94-203	E1 -1	Brunswick Pt. Range	89	95	ns	6.3034	0.46	57.1536	ns
94-204	E2 -2	Brunswick Pt. Range	91	97	ns	2.3216	0.17	21.0502	**
94-210	E3-1	Brunswick Pt. Range	80	85	ns	22.28	1.68	202.045	**
94-211	F1-1	Terry Cr.	81	86	@	0.1223	0.01	1.1086	**
94-212	F2-1	Dupree Cr.	0	0	@	1.528	0.12	13.8547	**
94-213	G1-1	Back River	96	103	ns	0.325	0.02	2.95285	**
94-214	G2-1	Back River	92	99	ns	73.9363	5.32	670.389	ns
94-215	G3-1	Back River	89	96	ns	13.064	1.00	118.453	*
94-216	Ref. No. Inlet					11.2882	0.83	102.408	ns
94-242	Ref. No. Inlet					10.7696	0.82	97.6491	ns
	Ref. Redfish Bay								
	Ref. No. Inlet								

Duplicates for averaged result represented above

		AVS
94-204	E2-2	6.34
94-204	E2-2	5.8

Appendix C. Method detection limits (MDLs) for organics and trace metals.		
Substance	Method of Analysis	MDL*
Fluorene	HPLC+GC-MS	5.7 ng/g
Phenanthrene	HPLC+GC-MS	2.7 ng/g
Anthracene	HPLC+GC-MS	8.3 ng/g
Fluoranthene	HPLC+GC-MS	5.9 ng/g
Pyrene	HPLC+GC-MS	7.3 ng/g
Benz(a)anthracene	HPLC+GC-MS	4.8 ng/g
Chrysene	HPLC+GC-MS	7.3 ng/g
Perylene	HPLC+GC-MS	5.4 ng/g
Benzo(b)fluoranthene	HPLC+GC-MS	8.8 ng/g
Benzo(k)fluoranthene	HPLC+GC-MS	5.3 ng/g
Benzo(a)pyrene	HPLC+GC-MS	7.4 ng/g
Dibenzo(a,h)anthracene	HPLC+GC-MS	7.3 ng/g
Benzo(g,h,i)perylene	HPLC+GC-MS	8.2 ng/g
HCB	GC-ECD	0.5 ng/g
y - HCH	GC-ECD	0.5 ng/g
Heptachlor	GC-ECD	0.7 ng/g
Aldrin	GC-ECD	0.5 ng/g
Heptachlor epoxide	GC-ECD	0.8 ng/g
2, 4'-DDE	GC-ECD	0.6 ng/g
cis-Chlordane	GC-ECD	0.8 ng/g
trans-Chlordane	GC-ECD	0.8 ng/g
Dieldrin	GC-ECD	1.0 ng/g
4, 4'-DDE	GC-ECD	0.9 ng/g
2, 4'-DDD	GC-ECD	2.3 ng/g
4, 4'-DDD	GC-ECD	0.9 ng/g
2, 4'-DDT	GC-ECD	0.8 ng/g
4, 4'-DDT	GC-ECD	0.9 ng/g
Mirex	GC-ECD	0.7 ng/g
PCB congeners (21)	GC-ECD	0.29-2.27 ng/g

Appendix C. continued		
Substance	Method of Analysis	MDL*
Cadmium	ICP	0.3 ug/g
Copper	ICP	0.2 ug/g
Lead	ICP	0.8 ug/g
Nickel	ICP	1.4 ug/g
Chromium	ICP	0.4 ug/g
Zinc	ICP	0.3 ug/g
Aluminum	ICP	882 g/kg
Iron	ICP	297 g/kg
Silver	GF-AA	0.1 ug/g
Manganese	ICP	0.3 ug/g
Arsenic	ICP	5.7 ug/g
Selenium	GF-AA	0.1 ug/g
Tin	ICP	7.8 ug/g
Lead	GF-AA	0.4 ug/g
Arsenic	GF-AA	0.1 ug/g
*MDLs established for PAHs from the standard deviations of the analyses of the spikes,		
for organochlorines as three times the standard deviation of repeated measures,		
and for metals as the mean blank plus 3 standard deviations		
(where mean blank is negative, MDL set as 0.0).		